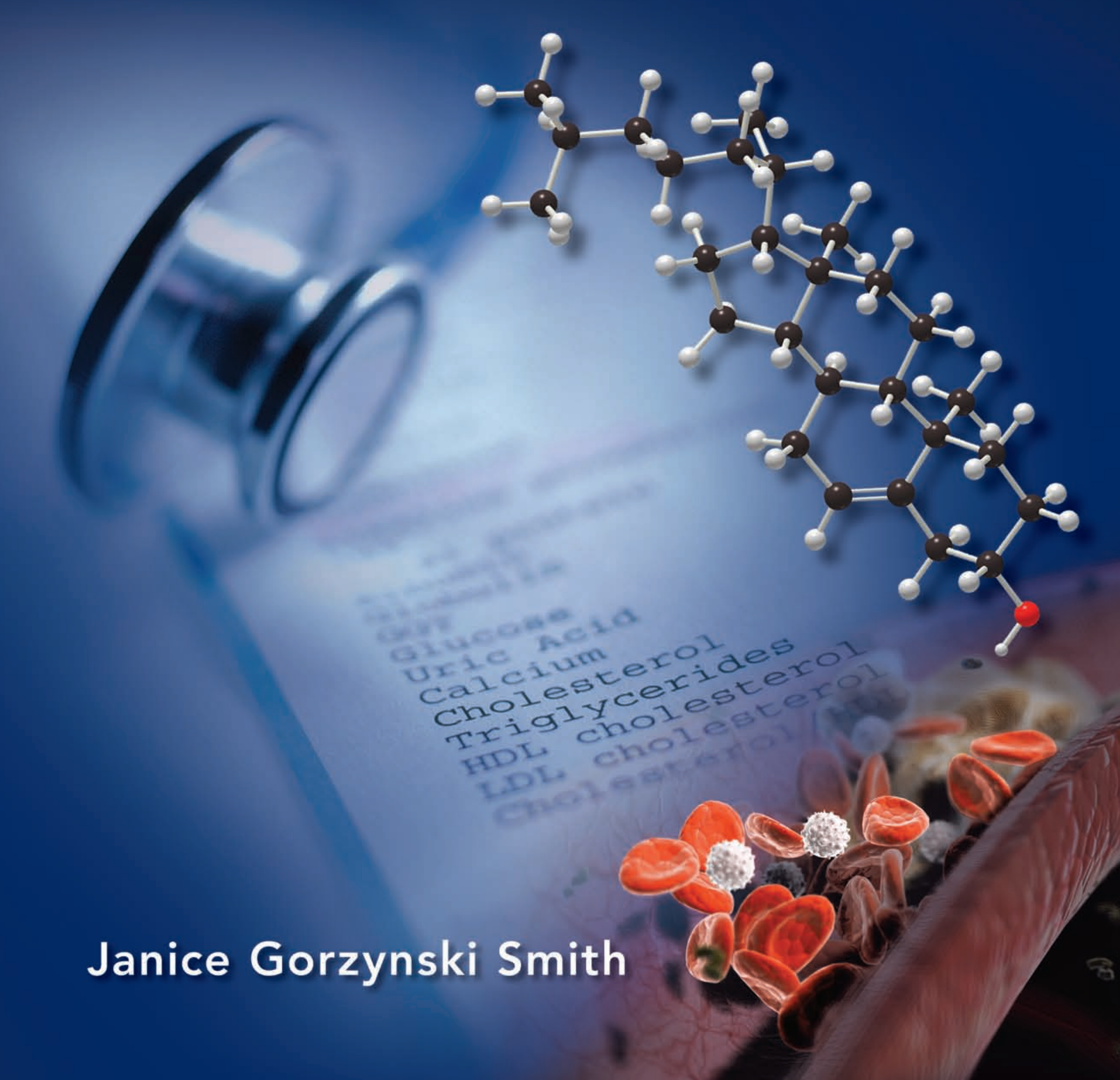
General, Organic, & Biological

CHEMISTRY



Janice Gorzynski Smith

Brief Contents

11

CHAPTER OUTLINE

CHAPTER GOALS

In this chapter you will learn how to:

1. Recognize the characteristic features of organic compounds
2. Predict the shape around atoms in organic molecules
3. Use shorthand methods to draw organic molecules
4. Recognize the common functional groups and understand their importance
5. Distinguish organic compounds from ionic inorganic compounds
6. Determine whether an organic compound is polar or nonpolar
7. Determine solubility properties of organic compounds
8. Determine whether a vitamin is fat soluble or water soluble



Vitamin A, a key component of the vision receptors in the eye, is synthesized in the body from β-carotene, the orange pigment found in carrots.

INTRODUCTION TO ORGANIC MOLECULES AND FUNCTIONAL GROUPS

CONSIDER for a moment the activities that occupied your past 24 hours. You likely showered with soap, drank a caffeinated beverage, ate at least one form of starch, took some medication, read a newspaper, listened to a CD, and traveled in a vehicle that had rubber tires and was powered by fossil fuels. If you did any *one* of these, your life was touched by organic chemistry. In Chapter 11, we learn about the characteristic features of organic molecules.

11.1 INTRODUCTION TO ORGANIC CHEMISTRY

What is organic chemistry?

- **Organic chemistry is the study of compounds that contain the element carbon.**

While it may seem odd that an entire discipline is devoted to the study of a single element in the periodic table, millions of organic compounds are known, far more than the inorganic compounds discussed in Chapters 1–10. **These organic chemicals affect virtually every facet of our lives, and for this reason, it is important and useful to know something about them.**

Clothes, foods, medicines, gasoline, refrigerants, and soaps are composed almost solely of organic compounds. Some, like cotton, wool, or silk are naturally occurring; that is, they can be isolated directly from natural sources. Others, such as nylon and polyester are synthetic, meaning they are produced by chemists in the laboratory. By studying the principles and concepts of organic chemistry, you can learn more about compounds such as these and how they affect the world around you. Figure 11.1 illustrates some common products of organic chemistry used in medicine.

FIGURE 11.1 Some Common Products of Organic Chemistry Used in Medicine

a. Oral contraceptives



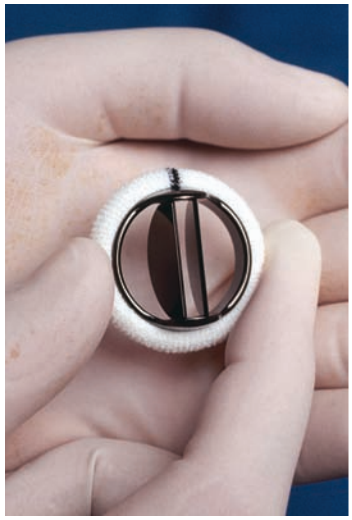
b. Plastic syringes



c. Antibiotics



d. Synthetic heart valves



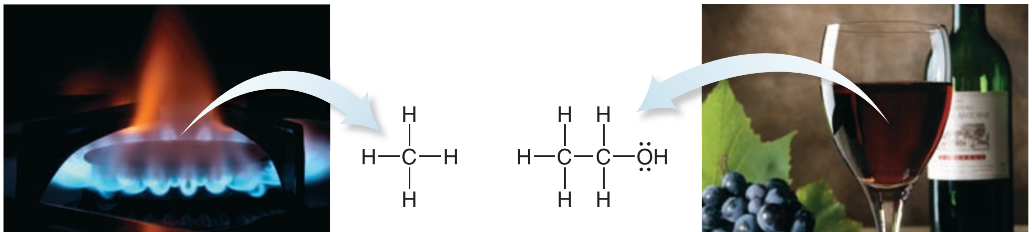
Organic chemistry has given us contraceptives, plastics, antibiotics, synthetic heart valves, and a myriad of other materials. Our lives would be vastly different today without these products of organic chemistry.

PROBLEM 11.1 Which molecular formulas represent organic compounds and which represent inorganic compounds?

a. C_6H_{12}
b. H_2O
c. KI
d. $MgSO_4$
e. CH_4O
f. NaOH

11.2 CHARACTERISTIC FEATURES OF ORGANIC COMPOUNDS

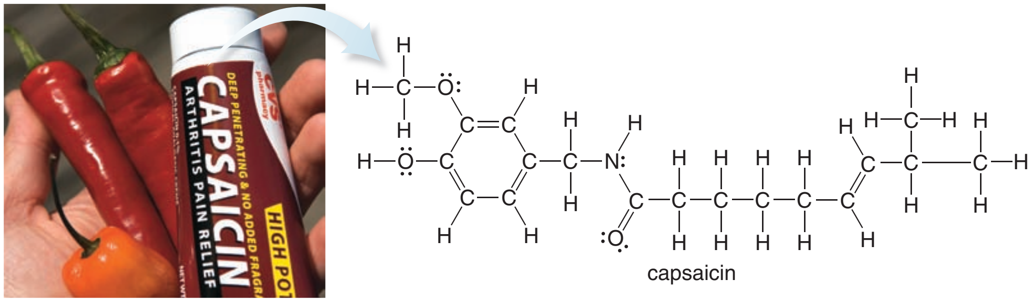
Perhaps the best way to appreciate the variety of organic molecules is to look at a few. Simple organic compounds that contain just one or two carbon atoms, respectively, are methane and ethanol.



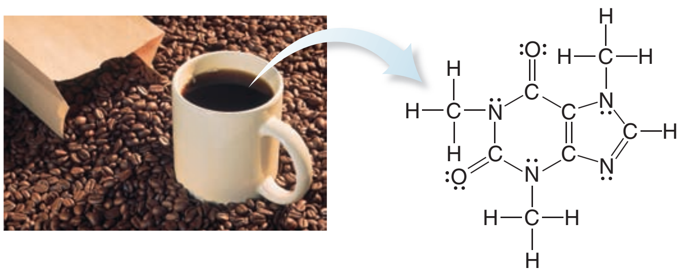
methane ethanol

Methane, the main component of natural gas, burns in the presence of oxygen. The natural gas we use today was formed by the decomposition of organic material millions of years ago. **Ethanol,** the alcohol present in wine and other alcoholic beverages, is formed by the fermentation of sugar. Ethanol can also be made in the lab by a totally different process. **Ethanol produced in the lab is identical to the ethanol produced by fermentation.**

Two more complex organic molecules are capsaicin and caffeine. **Capsaicin,** the compound responsible for the characteristic spiciness of hot peppers, is the active ingredient in several topical creams for pain relief. **Caffeine** is the bitter-tasting stimulant found in coffee, tea, cola beverages, and chocolate.



capsaicin



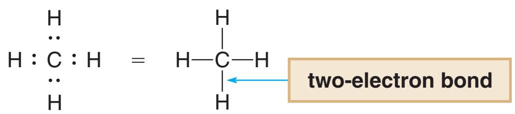
caffeine

What are the common features of these organic compounds?

[1] All organic compounds contain carbon atoms and most contain hydrogen atoms. Carbon always forms four covalent bonds, and hydrogen forms one covalent bond.

Carbon is located in group 4A of the periodic table, so a carbon atom has four valence electrons available for bonding (Section 4.1). Since hydrogen has a single valence electron, methane (CH_4) consists of four single bonds, each formed from one electron from a hydrogen atom and one electron from carbon.

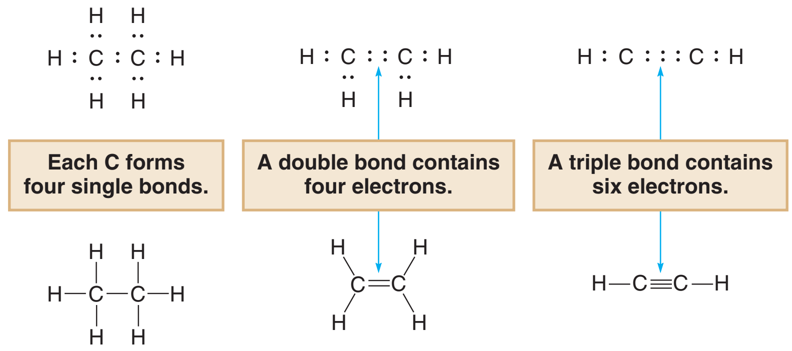
Remember that each solid line represents one two-electron bond.



methane

[2] Carbon forms single, double, and triple bonds to other carbon atoms.

When a compound contains two or more carbon atoms, the type of bonding is determined by the number of atoms around carbon. Consider the three compounds drawn below:

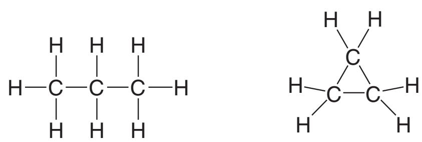


ethane ethylene acetylene

- **A C atom surrounded by four atoms forms four single bonds.** In ethane (C_2H_6), each carbon atom is bonded to three hydrogen atoms and one carbon atom. All bonds are single bonds.
- **A C atom surrounded by three atoms forms one double bond.** In ethylene (C_2H_4), each carbon atom is surrounded by three atoms (two hydrogens and one carbon); thus, each C forms a single bond to each hydrogen atom and a double bond to carbon.
- **A C atom surrounded by two atoms generally forms one triple bond.** In acetylene (C_2H_2), each carbon atom is surrounded by two atoms (one hydrogen and one carbon); thus, each C forms a single bond to hydrogen and a triple bond to carbon.

[3] Some compounds have chains of atoms and some compounds have rings.

For example, three carbon atoms can bond in a row to form propane, or form a ring called cyclopropane. Propane is the fuel burned in gas grills, and cyclopropane is an anesthetic.



propane C_3H_8 cyclopropane C_3H_6

[4] Organic compounds may also contain elements other than carbon and hydrogen. Any atom that is not carbon or hydrogen is called a *heteroatom.*

The most common heteroatoms are nitrogen, oxygen, and the halogens (F, Cl, Br, and I).

- Each heteroatom forms a characteristic number of bonds, determined by its location in the periodic table.
- The common heteroatoms also have nonbonding, lone pairs of electrons, so that each atom is surrounded by eight electrons.

The number of bonds formed by common elements was first discussed in Section 4.1.

Thus, nitrogen forms three bonds and has one lone pair of electrons, while oxygen forms two bonds and has two additional lone pairs. The halogens form one bond and have three additional lone pairs. Common bonding patterns for atoms in organic compounds are summarized in Table 11.1. Except for hydrogen, these common elements in organic compounds follow one rule in bonding:

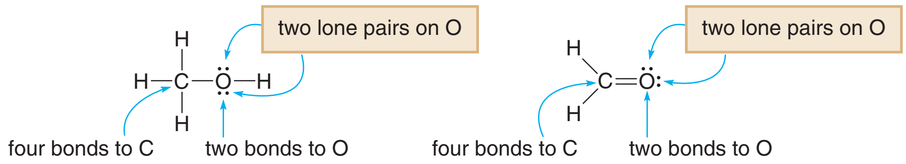
Number of bonds + **Number of lone pairs** = **4**

TABLE 11.1 Common Bonding Patterns for Atoms in Organic Compounds

	hydrogen	carbon	nitrogen	oxygen	halogen
	—H	—C— (four bonds)	—N̈— (three bonds, lone pair)	—Ö— (two bonds, two lone pairs)	—X: (one bond, three lone pairs) X = F, Cl, Br, I
Number of bonds	1	4	3	2	1
Number of nonbonded electron pairs	0	0	1	2	3

lone pairs of electrons

Oxygen and nitrogen form both single and multiple bonds to carbon. **The most common multiple bond between carbon and a heteroatom is a carbon–oxygen double bond (C═O).** The bonding patterns remain the same even when an atom is part of a multiple bond, as shown with methanol (CH_3OH) and formaldehyde ($H_2C{=}O$, a preservative).



methanol formaldehyde

These features explain why there are so many organic compounds: **Carbon forms four strong bonds with itself and other elements. Carbon atoms combine together to form rings and chains.**

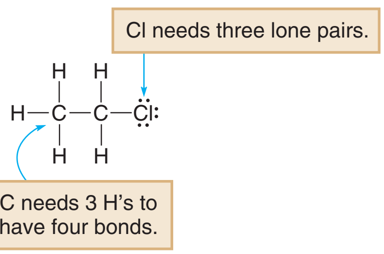
SAMPLE PROBLEM 11.1

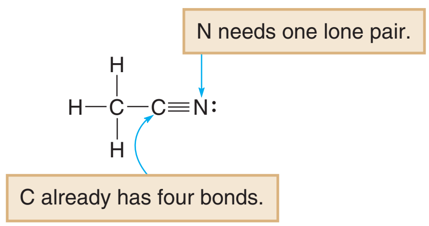
Draw in all H's and lone pairs in each compound.

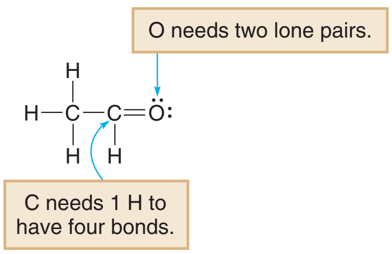
a. C—C—Cl b. C—C═O c. C—C≡N

ANALYSIS **Each C and heteroatom must be surrounded by eight electrons.** Use the common bonding patterns in Table 11.1 to fill in the needed H's and lone pairs. C needs four bonds; Cl needs one bond and three lone pairs; O needs two bonds and two lone pairs; N needs three bonds and one lone pair.

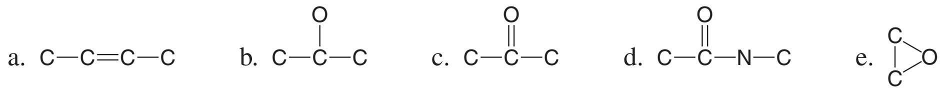
SOLUTION

a. 

c. 

b. 

PROBLEM 11.2 Fill in all H's and lone pairs in each compound.



11.3 SHAPES OF ORGANIC MOLECULES

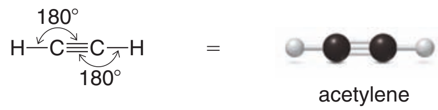
The shape around atoms in organic molecules is determined by counting groups using the principles of VSEPR theory (Section 4.6). Recall that a group is either another atom or a lone pair of electrons. **The most stable arrangement keeps these groups as far away from each other as possible.**



Because acetylene produces a very hot flame on burning, it is often used in welding torches.

- **An atom surrounded by two groups is linear and has a bond angle of 180°.**

Each carbon in acetylene (HC≡CH) is surrounded by two atoms and no lone pairs. Thus, each H—C—C bond angle is 180°, making all four atoms of acetylene linear.



two atoms around each C

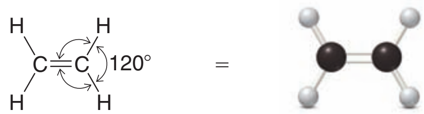
acetylene ball-and-stick model

- **An atom surrounded by three groups is trigonal planar and has a bond angle of 120°.**



Ethylene is an important starting material in the preparation of the plastic polyethylene.

Each carbon in ethylene ($CH_2{=}CH_2$) is surrounded by three atoms and no lone pairs. Thus, each H—C—C bond angle is 120°, and all six atoms of ethylene lie in one plane.

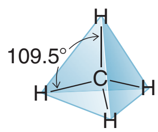


three atoms around each C

ethylene

- **An atom surrounded by four groups places these four groups at the corners of a tetrahedron, giving bond angles of approximately 109.5°.**

The carbon atom in methane (CH_4) is bonded to four hydrogen atoms, pointing to the corners of a tetrahedron.



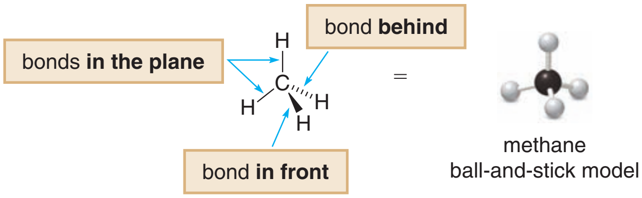
tetrahedral carbon

To draw the three-dimensional tetrahedron on a two-dimensional page, place two of the bonds in the plane of the page, one bond in front, and one bond behind. Then, use the drawing conventions first presented in Section 4.6:

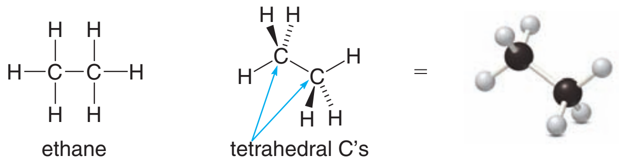
- **A solid line is used for bonds in the plane.**
- **A wedge is used for a bond in front of the plane.**
- **A dashed line is used for a bond behind the plane.**



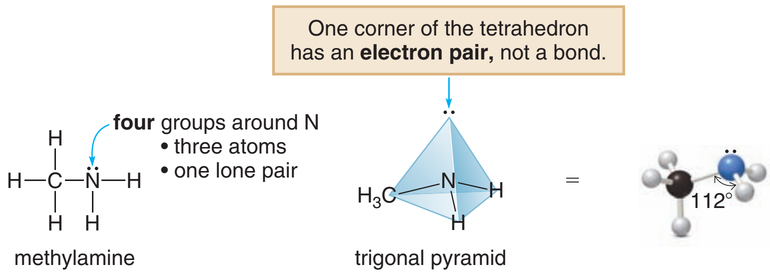
Ethane is a constituent of natural gas.



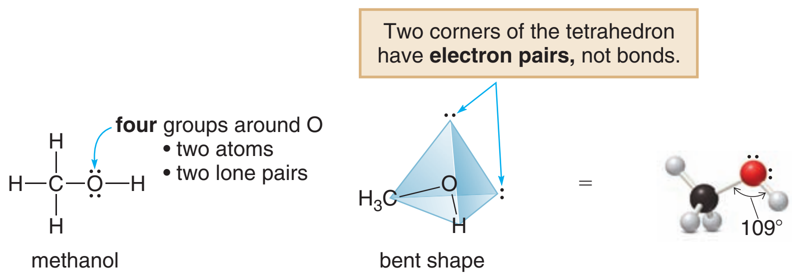
All carbons having four single bonds are tetrahedral. For example, each carbon of ethane is tetrahedral and can be drawn with two bonds in the plane, one in front on a wedge, and one behind on a dashed line.



Don't forget about the lone pairs of electrons on nitrogen and oxygen when determining the shape around these atoms. The N atom in methylamine (CH_3NH_2) is surrounded by three atoms and one lone pair—four groups. To keep these four groups as far apart as possible, each of these groups occupies the corner of a tetrahedron. In this way, the N atom of methylamine resembles the N atom of ammonia (NH_3) discussed in Section 4.6. The H—N—C bond angle of 112° is close to the theoretical tetrahedral bond angle of 109.5°. This molecular shape is referred to as a **trigonal pyramid,** because one of the groups around the N is a lone pair, not another atom.

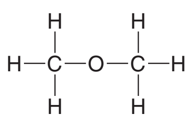


Similarly, the O atom in methanol (CH_3OH) is surrounded by two atoms and two lone pairs—four groups. To keep these groups as far apart as possible, each of these groups occupies the corner of a tetrahedron. In this way the O atom of methanol resembles the O atom of water (H_2O) discussed in Section 4.6. The C—O—H bond angle of 109° is close to the theoretical tetrahedral bond angle of 109.5°. Methanol has a bent molecular shape around O because two of the groups around oxygen are lone pairs. Table 11.2 summarizes the possible shapes around atoms in organic compounds.



SAMPLE PROBLEM 11.2

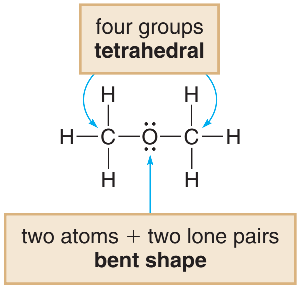
Determine the shape around each atom in dimethyl ether.



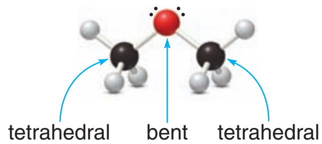
dimethyl ether

ANALYSIS First, draw in all lone pairs on the heteroatom. A heteroatom needs eight electrons around it, so add two lone pairs to O. Then count groups to determine the molecular shape.

SOLUTION

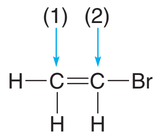


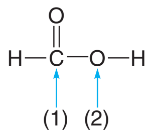
- Each C is surrounded by four atoms (3 H's and 1 O), making each C tetrahedral.
- The O atom is surrounded by 2 C's and two lone pairs (four groups), giving it a bent shape.
- This results in the following three-dimensional shape:

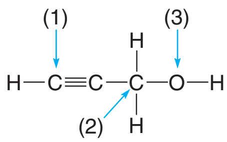


PROBLEM 11.3

Determine the shape around the indicated atoms in each compound. Don't forget to add electron pairs to heteroatoms before determining the shape.

a. 

c. 

b. 

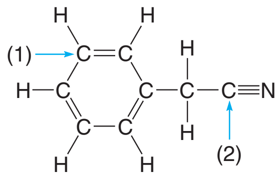
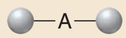
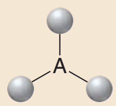
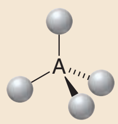
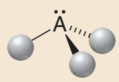
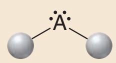
d. 

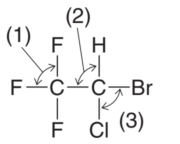
TABLE 11.2 Molecular Shape Around Atoms in Organic Compounds

Total Number of Groups	Number of Atoms	Number of Lone Pairs	Shape Around an Atom (A)	Approximate Bond Angle (°)
2	2	0	 linear	180
3	3	0	 trigonal planar	120
4	4	0	 tetrahedral	109.5
4	3	1	 trigonal pyramidal	~109.5[a]
4	2	2	 bent	~109.5[a]

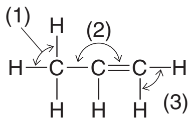
[a]The symbol "~" means approximately.

PROBLEM 11.4

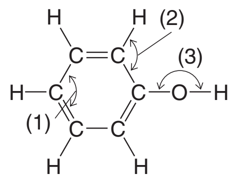
Predict the indicated bond angles in each compound.

a. 

halothane
(general anesthetic)

b. 

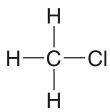
propene
(petroleum product)

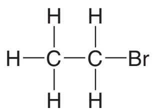
c. 

phenol
(antiseptic)

PROBLEM 11.5

Draw the structure of each compound using solid lines, wedges, and dashes to indicate the three-dimensional shape around each carbon.

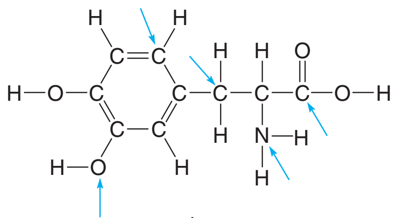
a. 

b. 

Don't let the size or complexity of an organic molecule intimidate you! Using the principles described in Section 11.3, you can predict the shape around any atom in any molecule no matter how complex it might be.

SAMPLE PROBLEM 11.3

L-Dopa is a drug used to treat Parkinson's disease. Give the shape around each indicated atom.



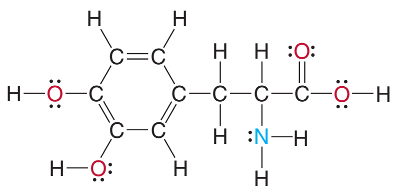
L-dopa

ANALYSIS

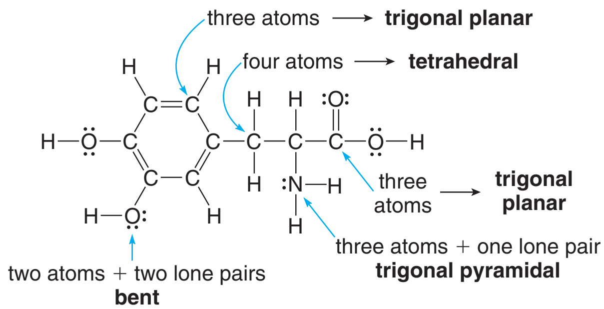
First, add lone pairs of electrons to each heteroatom so that it is surrounded by eight electrons. Each O gets two lone pairs and N gets one. Then count groups to predict shape.

SOLUTION

Adding electron pairs around O and N:



L-dopa



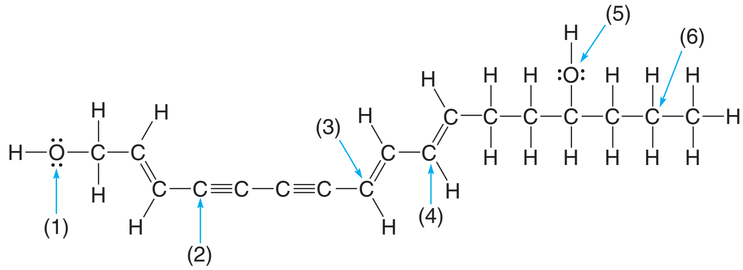
Pay special attention to the O and N atoms, and note the importance of adding the lone pairs before determining shape. O atoms are surrounded by ***four* groups—two atoms *and* two electron pairs**—giving them a bent shape. O atoms are *never* surrounded by two groups, making them linear.

PROBLEM 11.6

Enanthotoxin is a poisonous compound isolated from a common variety of hemlock grown in England. Predict the shape around the indicated atoms in enanthotoxin.



Hemlock is the source of the poison enanthotoxin.



enanthotoxin

11.4 DRAWING ORGANIC MOLECULES

Because organic molecules often contain many atoms, we need shorthand methods to simplify their structures. The two main types of shorthand representations used for organic compounds are **condensed structures** and **skeletal structures.**

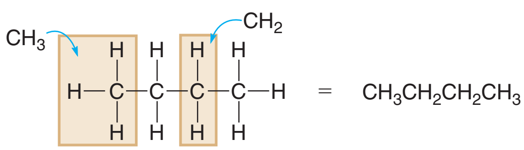
11.4A CONDENSED STRUCTURES

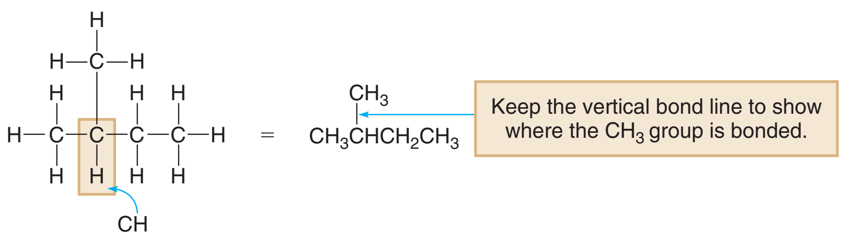
Condensed structures are most often used for a compound having a chain of atoms bonded together, rather than a ring. The following conventions are used.

- **All of the atoms are drawn in, but the two-electron bond lines are generally omitted.**
- **Lone pairs on heteroatoms are omitted.**

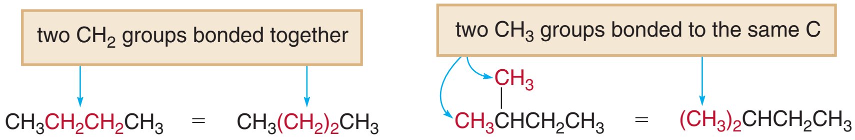
To interpret a condensed formula, it is usually best to start at the *left side* of the molecule and remember that the ***carbon atoms must have four bonds.***

- **A carbon bonded to 3 H's becomes CH_3.**
- **A carbon bonded to 2 H's becomes CH_2.**
- **A carbon bonded to 1 H becomes CH.**



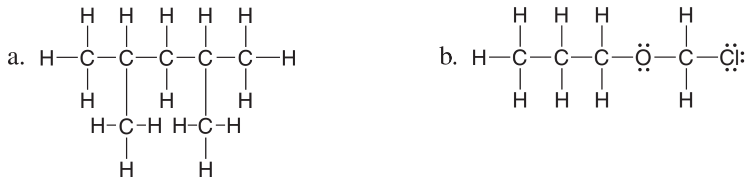


Sometimes these structures are further simplified by using parentheses around like groups. Two CH_2 groups bonded together become $(CH_2)_2$. Two CH_3 groups bonded to the same carbon become $(CH_3)_2C$.



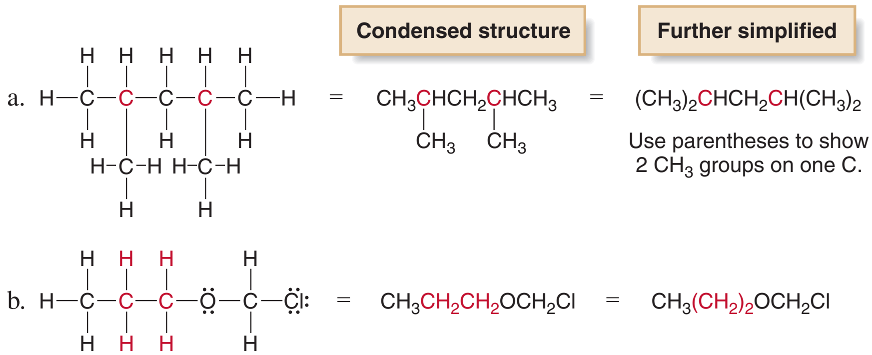
SAMPLE PROBLEM 11.4

Convert each compound into a condensed structure.



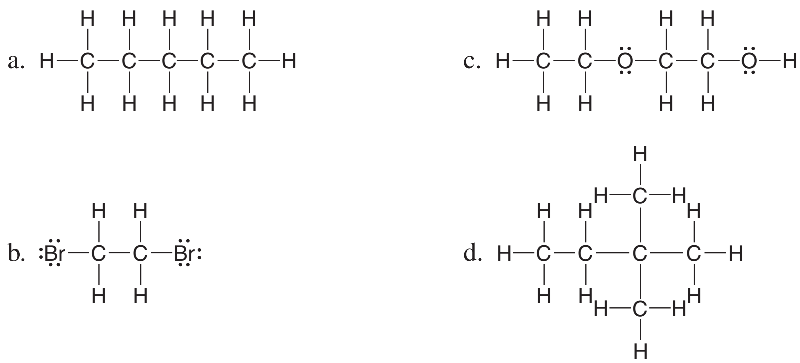
ANALYSIS Start at the left and proceed to the right, making sure that each carbon has four bonds. Omit lone pairs on the heteroatoms O and Cl. When like groups are bonded together or bonded to the same atom, use parentheses to further simplify the structure.

SOLUTION



PROBLEM 11.7

Convert each compound to a condensed formula.



PROBLEM 11.8

Convert each condensed formula to a complete structure.

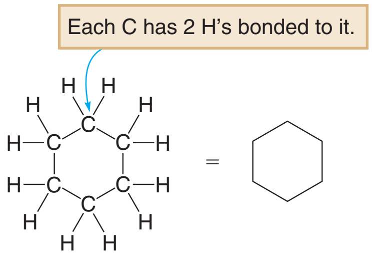
a. $CH_3(CH_2)_8CH_3$
b. $CH_3(CH_2)_4OH$
c. CH_3CCl_3
d. $CH_3(CH_2)_4CH(CH_3)_2$
e. $(CH_3)_2CHCH_2NH_2$

11.4B SKELETAL STRUCTURES

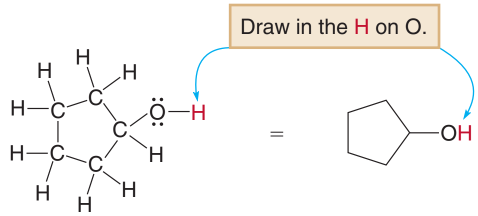
Skeletal structures are used for organic compounds containing both rings and chains of atoms. Three important rules are used in drawing them.

- **Assume there is a carbon atom at the junction of any two lines or at the end of any line.**
- **Assume there are enough hydrogens around each carbon to give it four bonds.**
- **Draw in all heteroatoms and the hydrogens directly bonded to them.**

Rings are drawn as polygons with a carbon atom "understood" at each vertex, as shown for cyclohexane and cyclopentanol. All carbons and hydrogens in these molecules are understood, except for H's bonded to heteroatoms.



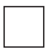
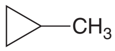
cyclohexane skeletal structure



cyclopentanol skeletal structure

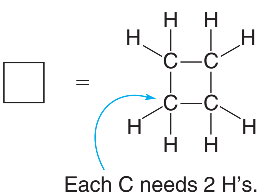
SAMPLE PROBLEM 11.5

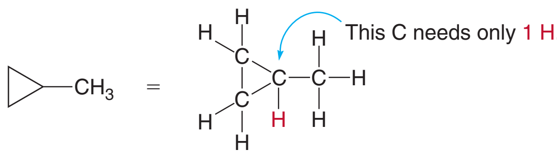
Convert each skeletal structure to a complete structure with all C's and H's drawn in.

a.  b. 

ANALYSIS To draw each complete structure, place a C atom at the corner of each polygon and add H's to give carbon four bonds.

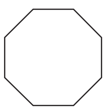
SOLUTION

a. 

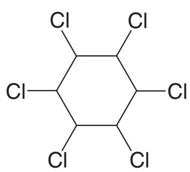
b. 

PROBLEM 11.9

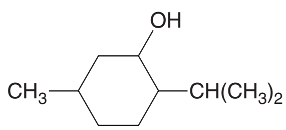
Convert each skeletal structure to a complete structure with all C's and H's drawn in. Add lone pairs on all heteroatoms.

a. 

cyclooctane

b. 

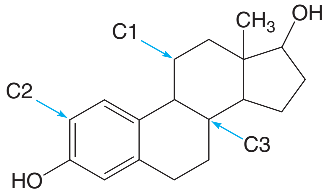
lindane
(an insecticide)

c. 

menthol
(isolated from peppermint)

SAMPLE PROBLEM 11.6

Shorthand structures for more complex organic compounds are drawn with the same principles used for simpler structures. Answer the following questions about estradiol, a female sex hormone that controls the development of secondary sex characteristics.



estradiol
(female sex hormone)

a. How many C atoms are present in estradiol?

b. How many H atoms are bonded to C1? C2? C3?

c. Draw a complete structure for estradiol, including all lone pairs on O atoms.

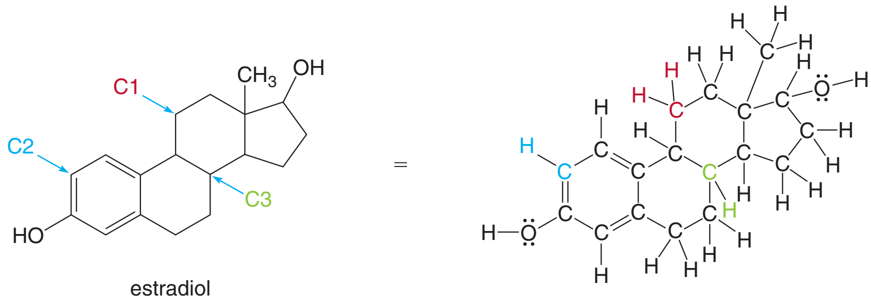
ANALYSIS Place a C atom at each corner of all polygons. Add enough H's to give each C four bonds. Each O needs two lone pairs to have eight electrons around it.

SOLUTION

a. Since each corner of a polygon represents a C, estradiol has a total of 18 C's.

b. C1, labeled in red (below), needs 2 H's to give it four bonds. C2, labeled in blue, needs 1 H to give it four bonds. C3, labeled in green, needs 1 H to give it four bonds.

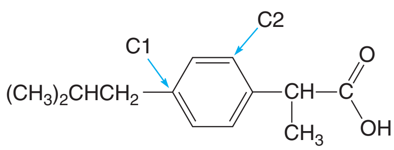
c.



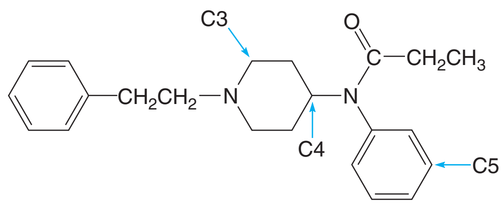
estradiol
(female sex hormone)

PROBLEM 11.10

How many H's are bonded to each indicated carbon (C1–C5) in the following drugs.



ibuprofen
(anti-inflammatory agent)



fentanyl
(narcotic pain reliever)

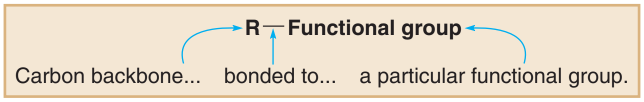
11.5 FUNCTIONAL GROUPS

In addition to strong C—C and C—H bonds, organic molecules may have other structural features as well. Although over 20 million organic compounds are currently known, only a limited number of common structural features, called **functional groups,** are found in these molecules.

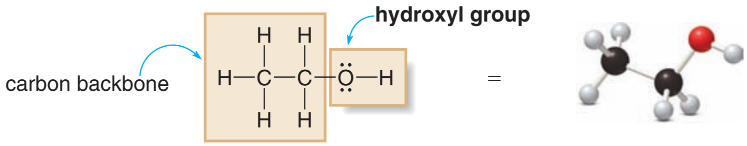
- **A *functional group* is an atom or a group of atoms with characteristic chemical and physical properties.**
- **A functional group contains a heteroatom, a multiple bond, or sometimes both a heteroatom *and* a multiple bond.**

A functional group determines a molecule's shape, properties, and the type of reactions it undergoes. A functional group behaves the same whether it is bonded to a carbon backbone having

as few as two or as many as 20 carbons. For this reason, we often abbreviate the carbon and hydrogen portion of the molecule by a capital letter **R,** and draw the **R** bonded to a particular functional group.



Ethanol (CH_3CH_2OH), for example, has two carbons and five hydrogens in its carbon backbone, as well as an OH group, a functional group called a **hydroxyl** group. The hydroxyl group determines the physical properties of ethanol as well as the type of reactions it undergoes. Moreover, any organic molecule containing a hydroxyl group has properties similar to ethanol. Compounds that contain a hydroxyl group are called **alcohols.**



ethanol

The most common functional groups can be subdivided into three types.

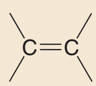
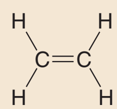
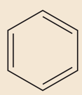
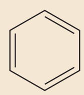
- Hydrocarbons
- Compounds containing a single bond to a heteroatom
- Compounds containing a C═O group

11.5A HYDROCARBONS

***Hydrocarbons* are compounds that contain only the elements of carbon and hydrogen,** as shown in Table 11.3.

- ***Alkanes*** have only C—C single bonds and no functional group. Ethane, **CH_3CH_3,** is a simple alkane.
- ***Alkenes*** have a C—C double bond as their functional group. Ethylene, **CH_2═CH_2,** is a simple alkene.
- ***Alkynes*** have a C—C triple bond as their functional group. Acetylene, **HC≡CH,** is a simple alkyne.
- ***Aromatic hydrocarbons*** contain a benzene ring, a six-membered ring with three double bonds.

TABLE 11.3 Hydrocarbons

Type of Compound	General Structure	Example	Functional Group
Alkane	R—H	CH_3CH_3	—
Alkene			Carbon–carbon double bond
Alkyne	—C≡C—	H—C≡C—H	Carbon–carbon triple bond
Aromatic compound			Benzene ring

CONSUMER NOTE

Polyethylene is a synthetic plastic first produced in the 1930s, initially used as insulating material for radar during World War II. It is now a plastic in milk containers, sandwich bags, and plastic wrapping. Over 100 billion pounds of polyethylene are manufactured each year.

ENVIRONMENTAL NOTE



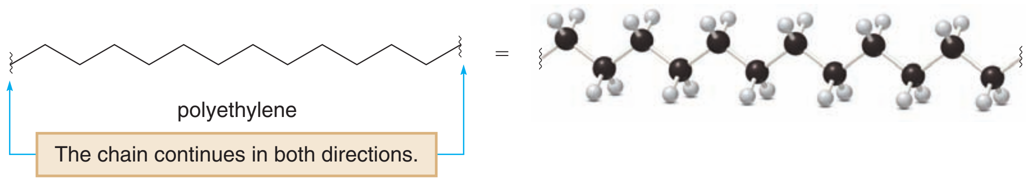
Shipments of wood coming to the United States from China are fumigated with CH_3Br (bromomethane) in an effort to prevent the Asian long-horned beetle from invading an environment in which it has no known predators.

HEALTH NOTE



Chloroethane, CH_3CH_2Cl, is used as a local anesthetic.

All hydrocarbons other than alkanes contain multiple bonds. Alkanes, which have no functional groups and therefore no reactive sites, are notoriously unreactive except under very drastic conditions. For example, **polyethylene** is a synthetic plastic and high molecular weight alkane, consisting of long chains of $—CH_2—$ groups bonded together, hundreds or even thousands of atoms long. Because it has no reactive sites, it is a very stable compound that does not readily degrade and thus persists for years in landfills.

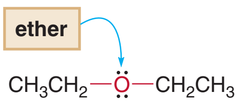


11.5B COMPOUNDS CONTAINING A SINGLE BOND TO A HETEROATOM

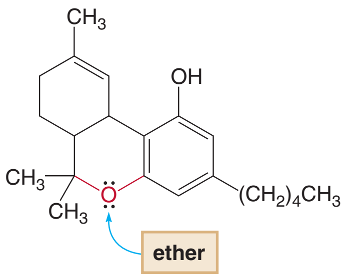
Several types of functional groups contain a carbon atom singly bonded to a heteroatom. Common examples include alkyl halides, alcohols, ethers, and amines, as shown in Table 11.4.

Several simple compounds in this category are widely used. Bromomethane (CH_3Br) is an alkyl halide that has been used to control the spread of the destructive Asian long-horned beetle to the United States. Chloroethane (CH_3CH_2Cl, commonly called ethyl chloride) is an alkyl halide used as a local anesthetic. When chloroethane is sprayed on a wound it quickly evaporates, causing a cooling sensation that numbs the site of injury.

Molecules containing these functional groups may be simple or very complex. It doesn't matter what else is present in other parts of the molecule. **Always dissect it into small pieces to identify the functional groups.** For example, diethyl ether, the first general anesthetic, is an ether because it has an O atom bonded to two C's. Tetrahydrocannabinol (THC), the active component in marijuana, is also an ether because it contains an O atom bonded to two carbon atoms. In this case the O atom is also part of a ring.



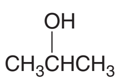
diethyl ether



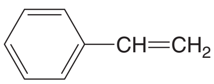
tetrahydrocannabinol (THC)

PROBLEM 11.11

Identify the functional groups in each compound. Some compounds contain more than one functional group.

a. 

2-propanol (disinfectant in rubbing alcohol)

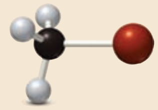
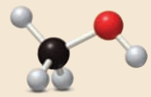
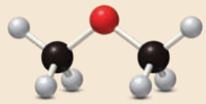
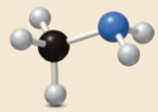
b. 

styrene (starting material used to synthesize Styrofoam)

c. $H_2NCH_2CH_2CH_2CH_2NH_2$

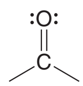
putrescine (putrid odor of rotting fish)

TABLE 11.4 Compounds Containing a Carbon–Heteroatom Single Bond

Type of Compound	General Structure	Example	3-D Structure	Functional Group
Alkyl halide	R—$\ddot{X}$: (X = F, Cl, Br, I)	CH_3—$\ddot{Br}$:		–X
Alcohol	R—$\ddot{O}$H	CH_3—$\ddot{O}$H		–OH hydroxyl group
Ether	R—$\ddot{O}$—R	CH_3—$\ddot{O}$—CH_3		–OR
Amine	R—$\ddot{N}H_2$ or $R_2\ddot{N}H$ or $R_3\ddot{N}$	CH_3—$\ddot{N}H_2$		$-NH_2$ amino group

11.5C COMPOUNDS CONTAINING A C=O GROUP

Many different kinds of compounds contain a carbon–oxygen double bond **(C=O, carbonyl group),** as shown in Table 11.5. Carbonyl compounds include aldehydes, ketones, carboxylic acids, esters, and amides. The type of atom bonded to the carbonyl carbon—hydrogen, carbon, or a heteroatom—determines the specific class of carbonyl compound.



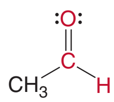
carbonyl group

=



Take special note of the condensed structures used to draw aldehydes, carboxylic acids, and esters.

- **An aldehyde has a hydrogen atom bonded directly to the carbonyl carbon.**

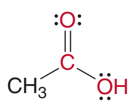


acetaldehyde

= CH_3CHO — C is bonded to both H and O.

condensed structure

- **A carboxylic acid contains an OH group bonded directly to the carbonyl carbon.**

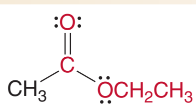


acetic acid

= CH_3COOH or CH_3CO_2H — C is bonded to both O atoms.

condensed structures

- **An ester contains an OR group bonded directly to the carbonyl carbon.**



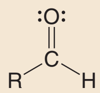
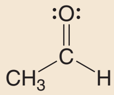
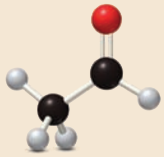
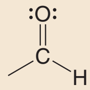
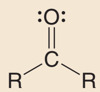
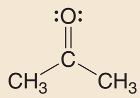
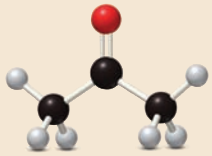
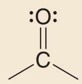
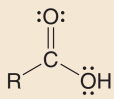
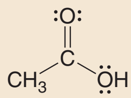
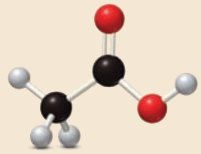
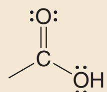
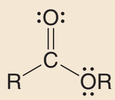
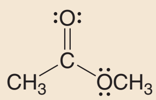
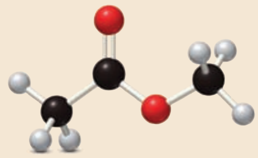
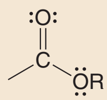
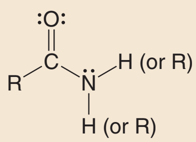
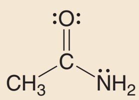
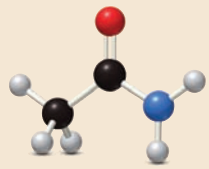
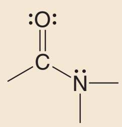
ethyl acetate

= $CH_3COOCH_2CH_3$ or $CH_3CO_2CH_2CH_3$

condensed structures

C is bonded to both O atoms.

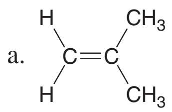
TABLE 11.5 Compounds Containing a C=O Group

Type of Compound	General Structure	Example	3-D Structure	Functional Group
Aldehyde				
Ketone				
Carboxylic acid				 carboxyl group
Ester				
Amide				

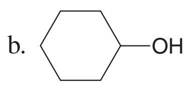
Carbonyl compounds occur widely in nature, and many are responsible for the characteristic odor or flavor of the fruits shown in Figure 11.2.

SAMPLE PROBLEM 11.7

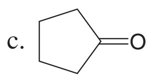
Identify the functional group in each compound.



A



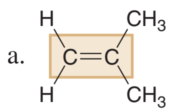
B



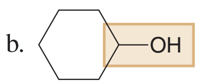
C

ANALYSIS Concentrate on the multiple bonds and heteroatoms and refer to Tables 11.3, 11.4, and 11.5.

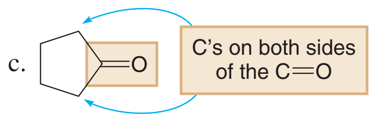
SOLUTION



A



B



C

A is a hydrocarbon with a carbon–carbon double bond, making it an alkene.

B has a carbon atom bonded to a hydroxyl group (OH), making it an alcohol.

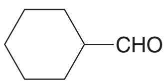
C contains a C=O. Since the carbonyl carbon is bonded to two other carbons in the ring, **C** is a ketone.

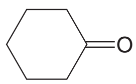
FIGURE 11.2 What We Eat—Naturally Occurring Carbonyl Compounds in Fruit

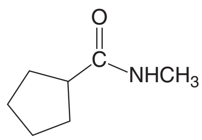


In addition to water, fruits (and other foods) contain a variety of organic compounds that give them taste, odor, texture, and nutritional value. Although one organic compound might be the major component in a food's flavor or odor, what we taste and smell is often a complex mixture of compounds. When even one of these components is missing, the odor and flavor can be somewhat different. This explains why artificial flavors and colors mimic, but don't really replace, the natural flavor.

PROBLEM 11.12 For each compound: [1] Identify the functional group; [2] draw out the complete compound, including lone pairs on heteroatoms.

a. 

c. 

e. 

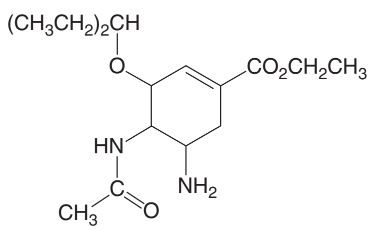
b. $CH_3CH_2CH_2CO_2H$

d. $CH_3CH_2CO_2CH_2CH_3$

PROBLEM 11.13 Identify the type of carbonyl group in each of the compounds in Figure 11.2.

Many useful organic compounds contain complex structures with two or more functional groups. Sample Problem 11.8 illustrates an example of identifying several functional groups in a single molecule.

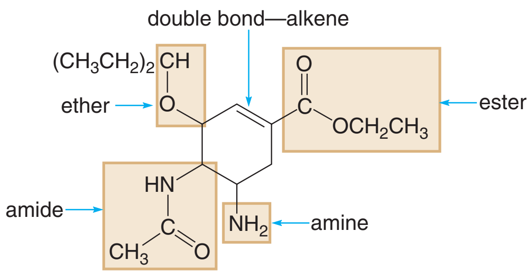
SAMPLE PROBLEM 11.8 Tamiflu is an antiviral drug effective against avian influenza. Identify all of the functional groups in Tamiflu.



Tamiflu

ANALYSIS To identify functional groups, look for multiple bonds and heteroatoms. With functional groups that contain O atoms, look at what is bonded to the O's to decide if the group is an alcohol, ether, or other group. With carbonyl-containing groups, look at what is bonded to the carbonyl carbon.

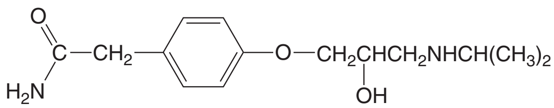
SOLUTION Re-draw Tamiflu to further clarify the functional groups:



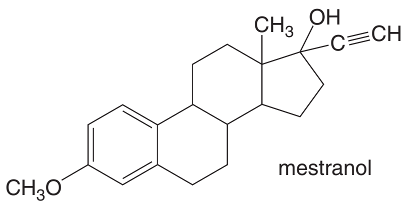
- Tamiflu contains a total of five functional groups: a carbon–carbon double bond (an alkene), ether, ester, amide, and amine.
- Note the difference between an amine and an amide. **An amine contains a N atom but no C=O. An amide contains a N atom directly bonded to a C=O.**

PROBLEM 11.14 Besides an ether group, tetrahydrocannabinol (Section 11.5B) contains three additional functional groups. Identify all of the functional groups in THC.

PROBLEM 11.15 Identify all of the functional groups in each drug. Atenolol is an antihypertensive agent; that is, it is used to treat high blood pressure. Mestranol is a synthetic estrogen used in oral contraceptives.

a. 

atenolol

b. 

mestranol

11.6 PROPERTIES OF ORGANIC COMPOUNDS

Because organic compounds are composed of covalent bonds, their properties differ a great deal from those of ionic inorganic compounds.

The intermolecular forces in covalent compounds were discussed in Section 7.7.

- **Organic compounds exist as discrete molecules with much weaker intermolecular forces—the forces that exist *between* molecules—than those seen in ionic compounds, which are held together by very strong interactions of oppositely charged ions.**

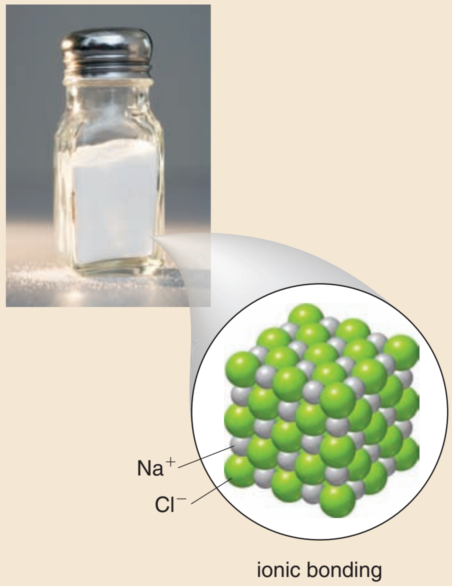
As a result, organic compounds resemble other covalent compounds in that they have much lower melting points and boiling points than ionic compounds. While ionic compounds are generally solids at room temperature, many organic compounds are liquids and some are even gases. Table 11.6 compares these and other properties of a typical organic compound (butane, $CH_3CH_2CH_2CH_3$) and a typical ionic inorganic compound (sodium chloride, NaCl).

Review Sections 4.6 and 4.7 on electronegativity, bond polarity, and polar molecules. Recall that **electronegativity** measures how much a particular atom "wants" the electron density in a bond.

11.6A POLARITY

Are organic compounds polar or nonpolar? That depends. Like other covalent compounds, the polarity of an organic compound is determined by two factors: the polarity of the individual

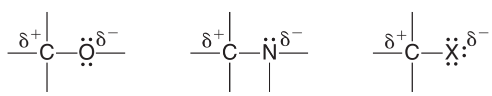
TABLE 11.6 Comparing the Properties of an Organic Compound ($CH_3CH_2CH_2CH_3$) and an Inorganic Compound (NaCl)

Property	$CH_3CH_2CH_2CH_3$ (An Organic Compound)	NaCl (An Inorganic Compound)
Bonding		
Physical state	Gas at room temperature	Solid at room temperature
Boiling point	Low (–0.5 °C)	High (1413 °C)
Melting point	Low (–138 °C)	High (801 °C)
Solubility in water	Insoluble	Soluble
Solubility in organic solvents	Soluble	Insoluble
Flammability	Flammable	Nonflammable

bonds and the overall shape of the molecule. **The polarity of an individual bond depends on the electronegativity of the atoms that form it.**

- A covalent bond is *nonpolar* when two atoms of identical or similar electronegativity are joined together. Thus, C—C and C—H bonds are nonpolar bonds.
- A covalent bond is *polar* when atoms of different electronegativity are joined together. Thus, bonds between carbon and common heteroatoms (N, O, and the halogens) are polar bonds.

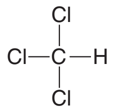
Since the common heteroatoms are *more* electronegative than carbon, these atoms pull electron density away from carbon, making it partially positive and the heteroatom partially negative.



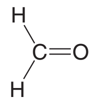
X = halogen

- The symbol δ^+ is given to the less electronegative atom (usually C or H).
- The symbol δ^- is given to the more electronegative atom (usually N, O, or a halogen).

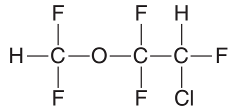
PROBLEM 11.16 Indicate the polar bonds in each compound. Label the bonds with δ$^+$ and δ$^-$.

a. 

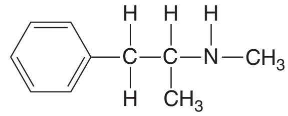
chloroform
(once used as an anesthetic)

b. 

formaldehyde
(preservative)

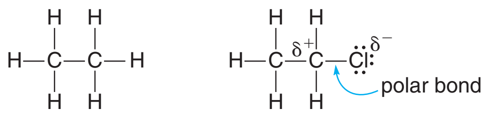
c. 

enflurane
(anesthetic)

d. 

methamphetamine
(illegal, addictive stimulant)

Hydrocarbons contain only nonpolar C—C and C—H bonds, so **hydrocarbons are nonpolar molecules.** In contrast, when an organic compound contains a *single* polar bond, as in the alkyl halide CH_3CH_2Cl, the molecule contains a net dipole, and is therefore a polar molecule.



ethane — no polar bonds, nonpolar molecule

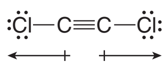
chloroethane — one polar bond, polar molecule

With organic compounds that have more than one polar bond, **the shape of the molecule determines the overall polarity.**

- **If the individual bond dipoles cancel in a molecule, the molecule is nonpolar.**
- **If the individual bond dipoles do not cancel, the molecule is polar.**

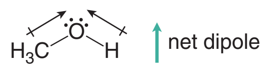
A bond dipole can be indicated by an arrow with the head of the arrow pointing towards the more electronegative element, and a perpendicular line drawn through the tail of the arrow (+⟶). Thus, dichloroacetylene (ClC≡CCl) is a linear molecule with two polar C—Cl bonds, but the individual bond dipoles are equal in magnitude and opposite in direction. As a result, dichloroacetylene is a *nonpolar* molecule. In contrast, methanol, CH_3OH, has two polar bonds (C—O and O—H), and a bent shape around oxygen (Section 11.3). The individual bond dipoles do *not* cancel, so CH_3OH is a *polar* molecule.

Two bond dipoles cancel.



dichloroacetylene
nonpolar molecule

Two bond dipoles do *not* cancel.



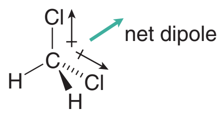
methanol
polar molecule

SAMPLE PROBLEM 11.9 Explain why dichloromethane (CH_2Cl_2), a solvent used in paint remover, is a polar molecule.

ANALYSIS CH_2Cl_2 has two polar C—Cl bonds. We must determine the shape of the molecule around the carbon atom and check whether the two bond dipoles cancel or reinforce.

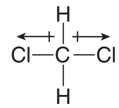
SOLUTION Since the C atom in CH_2Cl_2 is surrounded by four atoms, it is tetrahedral. The two bond dipoles do not cancel, and **CH_2Cl_2 is a polar molecule.**

Draw CH_2Cl_2 as a tetrahedron to see that the bond dipoles do not cancel.



polar molecule

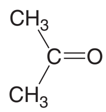
Do *not* draw CH_2Cl_2 as:



In this drawing it appears as if the bond dipoles cancel, but in reality they do *not*.

PROBLEM 11.17 Label each molecule as polar or nonpolar and explain your choice.

a. 

b. 

c. CCl_4

d. $CH_3CH_2CH_2NH_2$

PROBLEM 11.18 Explain why dimethyl ether (CH_3OCH_3) is a polar molecule.

11.6B SOLUBILITY

Review the general principles of solubility in Section 8.2.

Understanding the solubility properties of organic compounds allows us to understand many interesting phenomena. One rule governs solubility: **"Like dissolves like."** Three facts can then be used to explain the solubility of organic compounds.

- **Most organic compounds are soluble in organic solvents.**
- **Hydrocarbons and other nonpolar organic compounds are not soluble in water.**
- **Polar organic compounds are water soluble only if they are small and contain a nitrogen or oxygen atom that can hydrogen bond with water.**

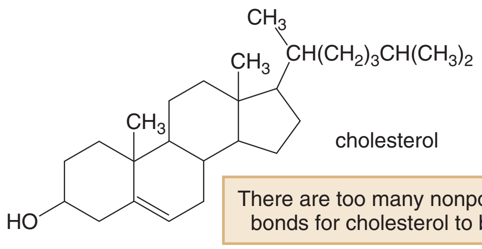
Three compounds—hexane, ethanol, and cholesterol—illustrate these principles. All of these compounds are organic and therefore soluble in an organic solvent like diethyl ether ($CH_3CH_2OCH_2CH_3$). Their water solubility depends on their polarity and size.

Since hexane ($CH_3CH_2CH_2CH_2CH_2CH_3$) is a nonpolar hydrocarbon, it is insoluble in water. Ethanol (CH_3CH_2OH), on the other hand, is water soluble because it is small and contains a polar OH group. The ethanol in gin dissolves in the water of tonic water, resulting in the alcoholic beverage called a "gin and tonic."

Cholesterol has 27 carbon atoms and only one OH group. Its nonpolar hydrocarbon part is too large to dissolve in water, making it water insoluble. As a result, cholesterol can't dissolve in the aqueous medium of the blood. When it must be transported through the body in the bloodstream, cholesterol is bound to other substances that are water soluble.

$CH_3CH_2—OH$
ethanol

H_2O soluble



cholesterol

There are too many nonpolar C—C and C—H bonds for cholesterol to be soluble in water.

H_2O insoluble

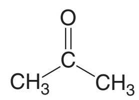
Table 11.7 summarizes the solubility characteristics of hexane, ethanol, and cholesterol.

TABLE 11.7 The Solubility Characteristics of Three Representative Organic Molecules

Compound	Solubility in an Organic Solvent	Solubility in Water
$CH_3CH_2CH_2CH_2CH_2CH_3$ Hexane	Soluble	Insoluble
CH_3CH_2OH Ethanol	Soluble	Soluble
Cholesterol	Soluble	Insoluble

PROBLEM 11.19 Predict the water solubility of each compound.

a. $CH_3(CH_2)_6CH_3$
octane
(gasoline component)

b. 

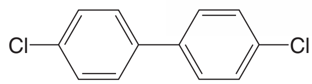
acetone
(solvent)

c. $CH_3(CH_2)_{16}CO_2H$
stearic acid
(a fatty acid)

11.6C FOCUS ON THE ENVIRONMENT ENVIRONMENTAL POLLUTANTS

MTBE (*tert*-butyl methyl ether) and 4,4'–dichlorobiphenyl (a PCB) demonstrate that solubility properties can help to determine the fate of organic pollutants in the environment.

$CH_3—O—C(CH_3)_3$
MTBE
tert-butyl methyl ether



4,4'-dichlorobiphenyl
(a PCB)

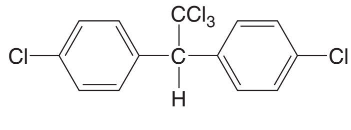
MTBE is a small polar organic molecule that has been used as a high-octane additive in unleaded gasoline. The use of MTBE, however, has now also caused environmental concern. Although MTBE is not toxic or carcinogenic, it has a distinctive, nauseating odor, and **it is water soluble.** Small amounts of MTBE have contaminated the drinking water in several California communities, making it unfit for consumption. These solubility properties of MTBE have now led to its ban in several states.

4,4'-Dichlorobiphenyl is one of a group of compounds called **PCB**s, which have been used in the manufacture of polystyrene coffee cups and other products. They have been released into the environment during production, use, storage, and disposal, making them one of the most widespread organic pollutants. **PCBs are insoluble in H_2O, but very soluble in organic media,** so

they are soluble in fatty tissue, including that found in all types of fish and birds around the world. Although not acutely toxic, ingesting large quantities of fish contaminated with PCBs has been shown to retard growth and memory retention in children.

PROBLEM 11.20

DDT is a persistent environmental pollutant once widely used as an insecticide. Using solubility principles, explain why shore birds that populate areas sprayed with DDT are found to have a high concentration of DDT in their tissues.



DDT

11.7 FOCUS ON HEALTH & MEDICINE VITAMINS

The name **vitamin** was first used in 1912 by the Polish chemist Casimir Funk, who called them *vitamines,* since he thought that they all contained an *amine* functional group. Later the word was shortened to vitamin, because some are amines but others, like vitamins A and C, are not.

Vitamins **are organic compounds needed in small amounts for normal cell function.** Our bodies cannot synthesize these compounds, so they must be obtained in our diet. Most vitamins are identified by a letter, such as A, C, D, E, and K. There are several different B vitamins, though, so a subscript is added to distinguish them—for example, B_1, B_2, and B_{12}.

Vitamins are classified on the basis of their solubility properties.

- **A *fat-soluble vitamin* dissolves in an organic solvent but is insoluble in water. Fat-soluble vitamins have many nonpolar C—C and C—H bonds and few polar functional groups.**
- **A *water-soluble vitamin* dissolves in water. Water-soluble vitamins have many polar bonds.**

Whether a vitamin is fat soluble or water soluble can be determined by applying the solubility principles discussed in Section 11.6. Vitamins A and C illustrate the differences between fat-soluble and water-soluble vitamins.

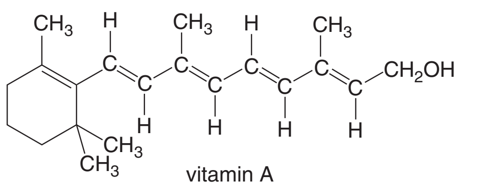
CONSUMER NOTE



Some anti-aging creams contain vitamin A.

11.7A VITAMIN A

Vitamin A, or **retinol,** is an essential component of the vision receptors in the eyes. It also helps to maintain the health of mucous membranes and the skin, so many anti-aging creams contain vitamin A. A deficiency of this vitamin leads to a loss of night vision.

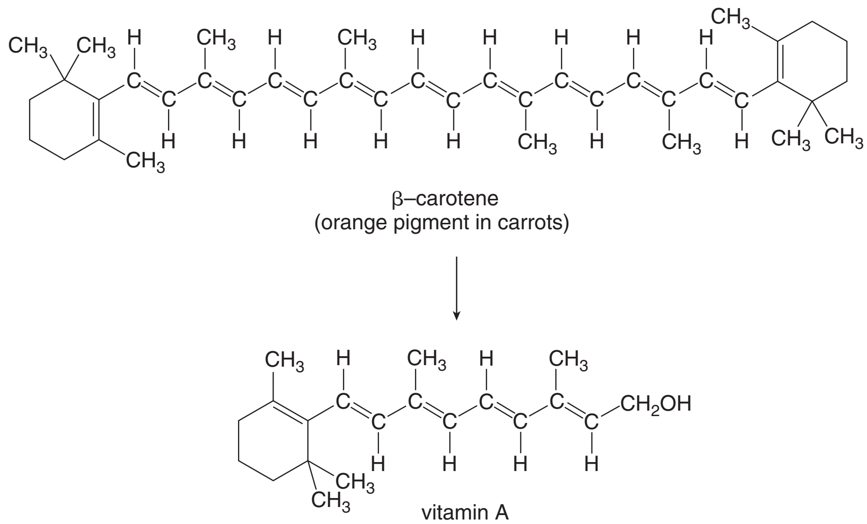


vitamin A

Vitamin A contains 20 carbons and a single OH group, making it **water insoluble.** Because it is organic, it is **soluble in any organic medium.** To understand the consequences of these solubility characteristics, we must learn about the chemical environment of the body.

About 70% of the body is composed of water. Fluids such as blood, gastric juices in the stomach, and urine are largely water with dissolved ions such as Na^+ and K^+. Vitamin A is insoluble in these fluids. There are also fat cells composed of organic compounds having C—C and C—H bonds. Vitamin A is soluble in this organic environment, and thus it is readily stored in these fat cells, particularly in the liver.

In addition to obtaining vitamin A directly from the diet, β-carotene, the orange pigment found in many plants including carrots, is readily converted to vitamin A in our bodies.



β–carotene
(orange pigment in carrots)

vitamin A

HEALTH NOTE





Vitamin C can be obtained from eating oranges and other citrus fruits. It can also be obtained by taking tablets that contain vitamin C synthesized in the laboratory. The vitamin C from both sources is exactly the same, so that "natural" vitamin C in oranges and "synthetic" vitamin C in tablets are identical.

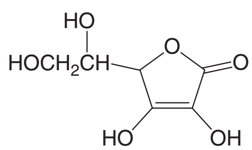
Eating too many carrots does not result in storing an excess of vitamin A. If you consume more β-carotene in carrots than you need, the body stores this precursor until it needs more vitamin A. Some of the stored β-carotene reaches the surface tissues of the skin, giving it an orange color. This phenomenon is harmless and reversible. When stored β-carotene is converted to vitamin A and is no longer in excess, these tissues will return to their normal hue.

Ingesting a moderate excess of vitamin A doesn't cause any harm, but a large excess causes headaches, loss of appetite, and even death. Early Arctic explorers who ate polar bear livers that contain an unusually large amount of vitamin A, are thought to have died from consuming too much vitamin A.

11.7B VITAMIN C

Although most animal species can synthesize vitamin C, humans, the Indian fruit bat, and the bulbul bird must obtain this vitamin from dietary sources. Citrus fruits, strawberries, tomatoes, and sweet potatoes are all excellent sources of vitamin C.

Vitamin C, or **ascorbic acid,** is important in the formation of collagen, a protein that forms the connective tissues of skin, muscle, and blood vessels. A deficiency of vitamin C causes scurvy, a common disease of sailors in the 1600s who had no access to fresh fruits on long voyages.

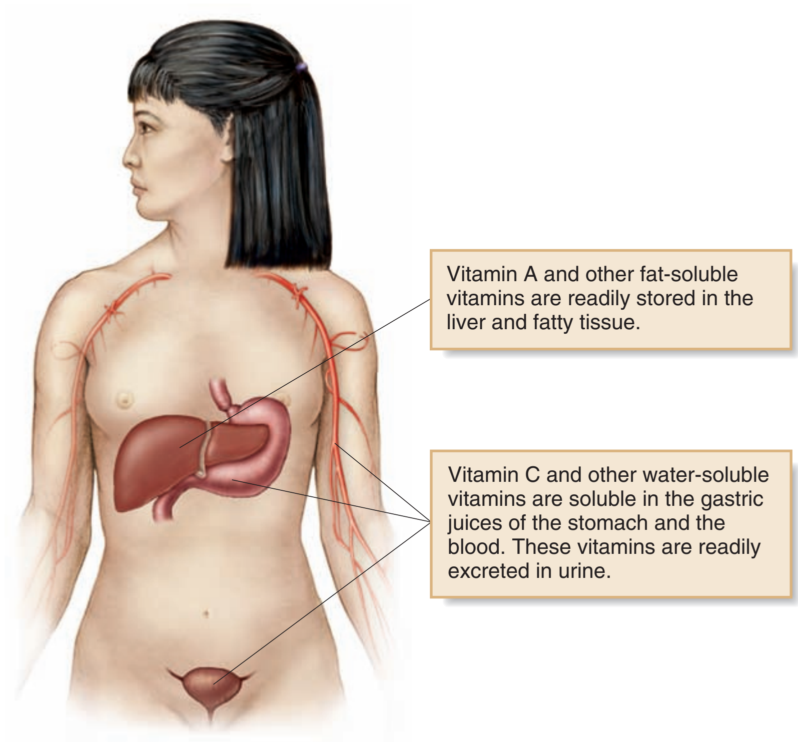


vitamin C
(ascorbic acid)

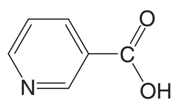
Vitamin C has six carbon atoms and six oxygen atoms, making it **water soluble.** Vitamin C thus dissolves in urine. Although it has been acclaimed as a deterrent for all kinds of diseases, from the common cold to cancer, the benefits of taking large amounts of vitamin C are not really known, since an excess of the minimum daily requirement is excreted unchanged in the urine.

The solubility characteristics of vitamins A and C are shown in Figure 11.3.

FIGURE 11.3 Solubility Characteristics of Vitamins A and C

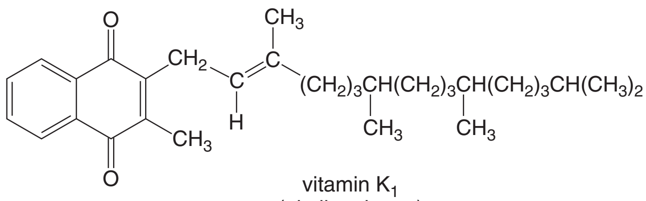


PROBLEM 11.21 Predict the solubility of vitamin B_3 in water.



vitamin B_3
(niacin)

PROBLEM 11.22 Predict the solubility of vitamin K_1 in water and in organic solvents.



vitamin K_1
(phylloquinone)

CHAPTER HIGHLIGHTS

KEY TERMS

Alcohol (11.5)
Aldehyde (11.5)
Alkane (11.5)
Alkene (11.5)
Alkyl halide (11.5)
Alkyne (11.5)
Amide (11.5)
Amine (11.5)
Amino group (11.5)
Aromatic compound (11.5)
Carbonyl group (11.5)
Carboxyl group (11.5)
Carboxylic acid (11.5)
Condensed structure (11.4)
Ester (11.5)
Ether (11.5)
Fat-soluble vitamin (11.7)
Functional group (11.5)
Heteroatom (11.2)
Hydrocarbon (11.5)
Hydroxyl group (11.5)
Ketone (11.5)
"Like dissolves like" (11.6)
Nonpolar molecule (11.6)
Organic chemistry (11.1)
Polar molecule (11.6)
Skeletal structure (11.4)
Vitamin (11.7)
Water-soluble vitamin (11.7)

KEY CONCEPTS

❶ What are the characteristic features of organic compounds? (11.2)

- Organic compounds contain carbon atoms and most contain hydrogen atoms. Carbon forms four bonds.
- Carbon forms single, double, and triple bonds to itself and other atoms.
- Carbon atoms can bond to form chains or rings.
- Organic compounds often contain heteroatoms, commonly N, O, and the halogens.

❷ How can we predict the shape around an atom in an organic molecule? (11.3)

- The shape around an atom is determined by counting groups, and then arranging them to keep them as far away from each other as possible.

Number of groups	Number of atoms	Number of lone pairs	Shape	Bond angle	Example
2	2	0	Linear	180°	$HC{\equiv}CH$
3	3	0	Trigonal planar	120°	$CH_2{=}CH_2$
4	4	0	Tetrahedral	109.5°	CH_3CH_3
4	3	1	Trigonal pyramidal	~109.5°	CH_3NH_2 (N atom)
4	2	2	Bent	~109.5°	CH_3OH (O atom)

❸ What shorthand methods are used to draw organic molecules? (11.4)

- In condensed structures, atoms are drawn in but the two-electron bonds are generally omitted. Lone pairs are omitted as well. Parentheses are used around like groups bonded together or to the same atom.
- Three assumptions are used in drawing skeletal structures: [1] There is a carbon at the intersection of two lines or at the end of any line. [2] Each carbon has enough hydrogens to give it four bonds. [3] Heteroatoms and the hydrogens bonded to them are drawn in.

❹ What is a functional group and why are functional groups important? (11.5)

- A functional group is an atom or a group of atoms with characteristic chemical and physical properties.
- A functional group determines all of the properties of a molecule—its shape, physical properties, and the type of reactions it undergoes.

❺ How do organic compounds differ from ionic inorganic compounds? (11.6)

- The main difference between organic compounds and ionic inorganic compounds is their bonding. Organic compounds are composed of discrete molecules with covalent bonds. Ionic inorganic compounds are composed of ions held together by the strong attraction of oppositely charged ions. Other properties that are consequences of these bonding differences are summarized in Table 11.6.

❻ How can we determine if an organic molecule is polar or nonpolar? (11.6A)

- A nonpolar molecule has either no polar bonds or two or more bond dipoles that cancel.
- A polar molecule has either one polar bond, or two or more bond dipoles that do not cancel.

❼ What are the solubility properties of organic compounds? (11.6B)

- Most organic molecules are soluble in organic solvents.
- Hydrocarbons and other nonpolar organic molecules are not soluble in water.
- Polar organic molecules are water soluble only if they are small and contain a nitrogen or oxygen atom that can hydrogen bond with water.

❽ What are vitamins and when is a vitamin fat soluble or water soluble? (11.7)

- A vitamin is an organic compound that cannot be synthesized by the body but is needed in small amounts for cell function.
- A fat-soluble vitamin has many nonpolar C—C and C—H bonds and few polar bonds, making it insoluble in water.
- A water-soluble vitamin has many polar bonds, so it dissolves in water.

PROBLEMS

Selected in-chapter and end-of-chapter problems have brief answers provided in Appendix B.

General Characteristics of Organic Molecules

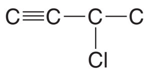
11.23 Which molecular formulas represent organic compounds and which represent inorganic compounds: (a) H_2SO_4; (b) Br_2; (c) C_5H_{12}?

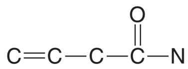
11.24 Which molecular formulas represent organic compounds and which represent inorganic compounds: (a) LiBr; (b) HCl; (c) CH_5N?

11.25 Complete each structure by filling in all H's and lone pairs.

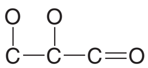
a. C—C=C—C≡C

b. C=C—C—O

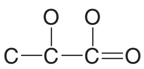
c. 

d. 

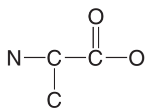
11.26 Complete each structure by filling in all H's and lone pairs.

a. 

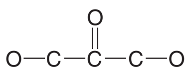
glyceraldehyde
(simple carbohydrate)

b. 

lactic acid
(product of carbohydrate metabolism)

c. 

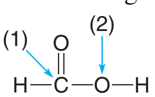
alanine
(amino acid in proteins)

d. 

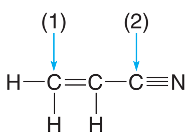
dihydroxyacetone
(ingredient in artificial tanning agents)

Predicting Shape and Bond Angles

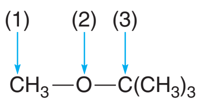
11.27 Determine the shape around the indicated atoms in each compound. Don't forget to add lone pairs to heteroatoms before determining the shape around them.

a. 

formic acid
(responsible for the sting of some ants)

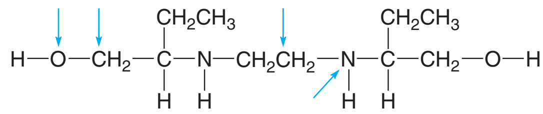
b. 

acrylonitrile
(used to prepare Orlon fibers)

c. 

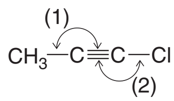
MTBE
(gasoline additive)

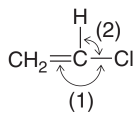
11.28 Ethambutol is a drug used to treat tuberculosis. Determine the shape around the indicated atoms in ethambutol. Don't forget to add lone pairs to heteroatoms before determining the shape around them.

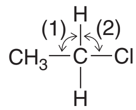


ethambutol

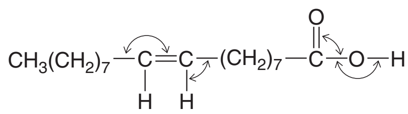
11.29 Predict the indicated bond angles in each compound.

a. 

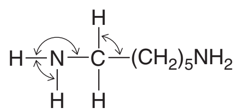
b. 

c. 

11.30 Predict the indicated bond angles in each compound. Don't forget to add lone pairs to heteroatoms before determining the shape around them.

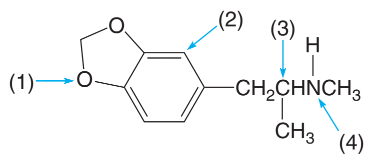
a. 

oleic acid
(fatty acid in vegetable oil)

b. 

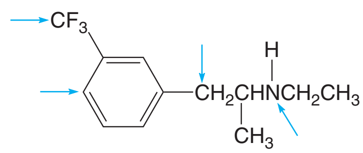
1,6-diaminohexane
(used to synthesize nylon)

11.31 "Ecstasy" is a widely used illegal stimulant. Determine the shape around each indicated atom.



MDMA
"Ecstasy"

11.32 Fenfluramine is one component of the appetite suppressant Fen–Phen, which was withdrawn from the market in 1997 after it was shown to damage the heart valves in some patients. Determine the shape around each indicated atom.



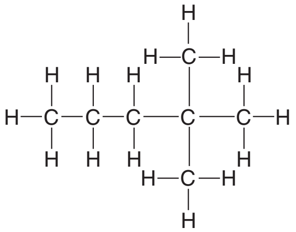
fenfluramine

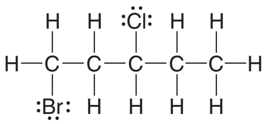
11.33 Explain why each C—C—C bond angle in benzene (Table 11.3) is 120°.

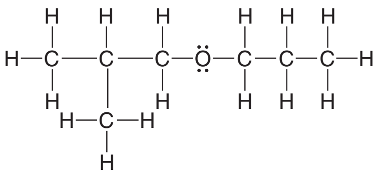
11.34 Hexachloroethane ($Cl_3C—CCl_3$), an alkyl chloride with a camphor-like odor, is a derivative of ethane (CH_3CH_3), formed by replacing each H by a Cl atom. Draw the structure of hexachloroethane using solid lines, wedges, and dashes to indicate the three-dimensional shape around each atom.

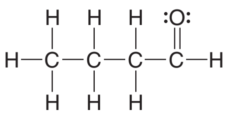
Drawing Organic Molecules

11.35 Convert each compound to a condensed structure.

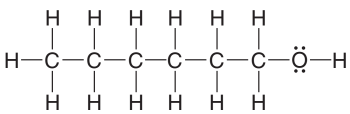
a. 

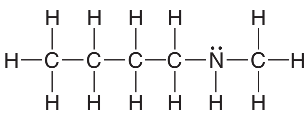
b. 

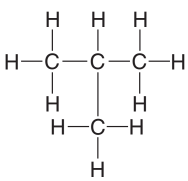
c. 

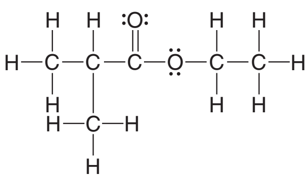
d. 

11.36 Convert each compound to a condensed structure.

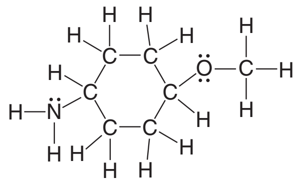
a. 

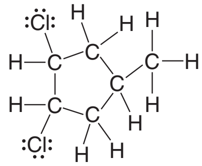
b. 

c. 

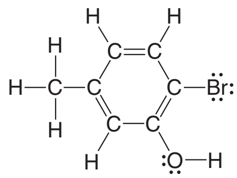
d. 

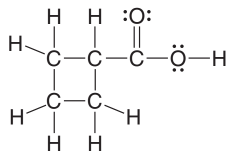
11.37 Convert each compound to a skeletal structure.

a. 

b. 

11.38 Convert each compound to a skeletal structure.

a. 

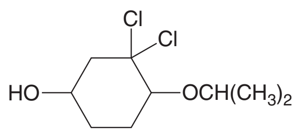
b. 

11.39 Convert each shorthand structure to a complete structure with all atoms and lone pairs drawn in.

a. $(CH_3)_2CH(CH_2)_6CH_3$

b. $(CH_3)_3COH$

c. $CH_3CO_2(CH_2)_3CH_3$

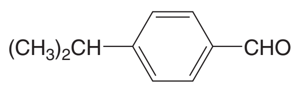
d. 

11.40 Convert each shorthand structure to a complete structure with all atoms and lone pairs drawn in.

a. $(CH_3)_2CHO(CH_2)_4CH_3$

b. $(CH_3)_3C(CH_2)_3CBr_3$

c. $(CH_3)_2CHCONH_2$

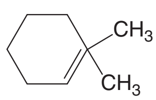
d. 

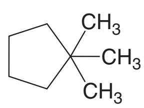
11.41 What is wrong in each of the following shorthand structures?

a. $(CH_3)_3CHCH_2CH_3$

b. $CH_3(CH_2)_4CH_3OH$

c. $(CH_3)_2C{=}CH_3$

d. 

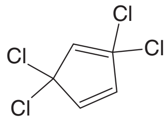
e. 

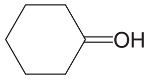
11.42 What is wrong in each of the following shorthand structures?

a. $HC\equiv CCH_2C=CH_2$

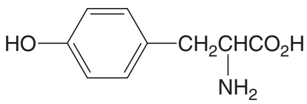
b. $CH_3C\equiv C(CH_3)_2$

c. $HC\equiv CCH_2C(CH_3)_2$

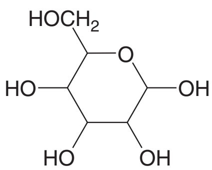
d. 

e. 

11.43 Convert the shorthand structure of each biologically active compound to a complete structure with all atoms and lone pairs drawn in. Tyrosine is one of the 20 amino acids used for protein synthesis. Glucose is the most common simple carbohydrate.

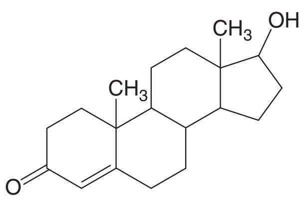
a. 

tyrosine

b. 

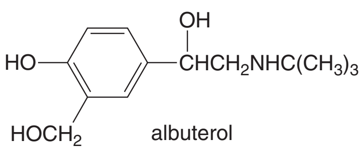
glucose

11.44 Testosterone is synthesized in the testes and controls the development of the secondary sex characteristics in males. Draw a complete structure of testosterone with all atoms and lone pairs.



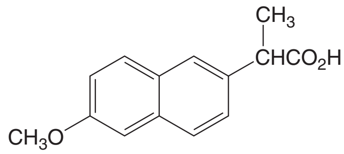
testosterone

11.45 Albuterol (trade names: Proventil and Ventolin) is a bronchodilator, a drug that widens airways, thus making it an effective treatment for individuals suffering from asthma. Draw a complete structure for albuterol with all atoms and lone pairs.



albuterol

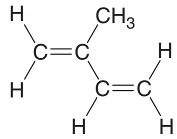
11.46 Naproxen is the anti-inflammatory agent in Aleve and Naprosyn. Draw a complete structure for naproxen including all atoms and lone pairs.



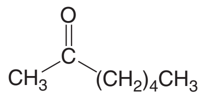
naproxen

Functional Groups

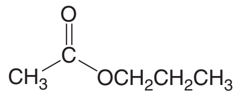
11.47 Identify the functional groups in each molecule.

a. 

isoprene
(emitted by plants)

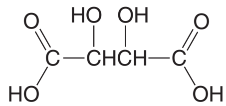
b. 

2-heptanone
(from blue cheese)

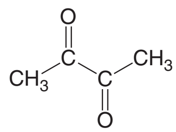
c. 

propyl acetate
(from pears)

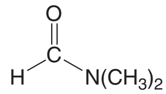
11.48 Identify the functional groups in each molecule.

a. 

tartaric acid
(from grapes)

b. 

butanedione
(component of butter flavor)

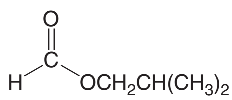
c. 

dimethylformamide
(solvent)

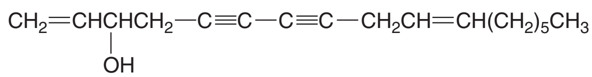
11.49 Identify the functional groups in each molecule.

a. $HOCH_2CH_2OH$

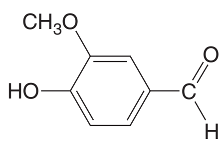
ethylene glycol
(used in antifreeze)

b. 

isobutyl formate
(odor of raspberries)

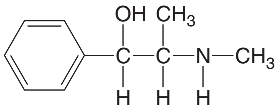
c. 

carotatoxin
(neurotoxin from carrots)

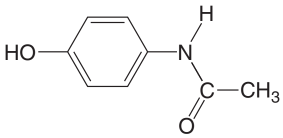
d. 

vanillin
(isolated from vanilla beans)

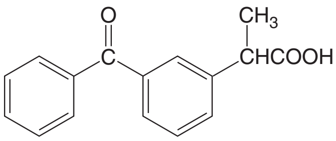
11.50 Identify the functional groups in each drug.

a. 

pseudoephedrine
(nasal decongestant)

b. 

acetaminophen
(analgesic in Tylenol)

c. 

ketoprofen
(analgesic)

11.51 Describe how the functional groups in an alcohol and ether differ. Give an example of an alcohol with two carbons and an ether with two carbons.

11.52 Describe how the functional groups in an amine and an amide differ. Give an example of an amine with two carbons and an amide with two carbons.

11.53 Describe how the functional groups in a carboxylic acid and an ester differ. Give an example of a carboxylic acid with three carbons and an ester with three carbons.

11.54 Describe how the functional groups in an aldehyde and a ketone differ. Give an example of an aldehyde with three carbons and a ketone with three carbons.

11.55 Draw an organic compound that fits each of the following criteria.

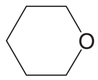
a. a hydrocarbon having molecular formula C_3H_4 that contains a triple bond
b. an alcohol containing three carbons
c. an aldehyde containing three carbons
d. a ketone having molecular formula C_4H_8O
e. an ester containing a CH_3 group bonded to the ester O atom

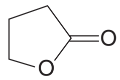
11.56 Draw an organic compound that fits each of the following criteria.

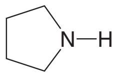
a. an amine containing two CH_3 groups bonded to the N atom
b. an alkene that has the double bond in a ring
c. an ether having two different R groups bonded to the ether oxygen
d. an amide that has molecular formula C_3H_7NO
e. a compound that contains an amino group bonded to a benzene ring

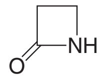
11.57 Draw the structure of an alkane, an alkene, and an alkyne, each having five carbon atoms. What is the molecular formula for each compound?

11.58 Some functional groups can occur as part of a ring. Although these functional groups might look quite different compared to the functional group in a molecule that has no ring, their properties and reactions are the same. Identify the functional group in each cyclic molecule.

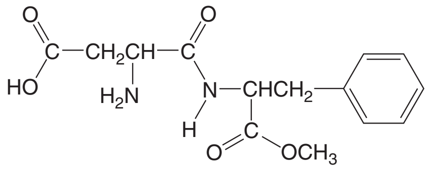
a. 

c. 

b. 

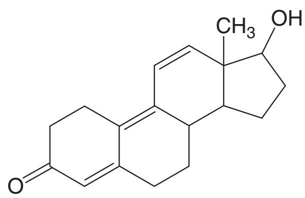
d. 

11.59 Aspartame (trade name NutraSweet) is a widely used substitute sweetener, 180 times sweeter than table sugar. Identify the functional groups in aspartame.



aspartame

11.60 Trenbolone is a synthetic anabolic steroid used by weight lifters and body builders to increase muscle mass. Identify the functional groups in trenbolone.



trenbolone

Properties of Organic Compounds

11.61 You are given two unlabeled bottles of solids, one containing sodium chloride (NaCl) and one containing cholesterol ($C_{27}H_{46}O$, Section 11.6B). You are also given two labeled bottles of liquids, one containing water and one containing dichloromethane (CH_2Cl_2). How can you determine which solid is sodium chloride and which solid is cholesterol?

11.62 State how potassium iodide (KI) and pentane ($CH_3CH_2CH_2CH_2CH_3$) differ with regards to each of the following properties: (a) type of bonding; (b) solubility in water; (c) solubility in an organic solvent; (d) melting point; (e) boiling point.

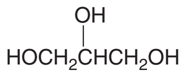
11.63 Why do we need to know the shape of a molecule with polar bonds before deciding if the molecule is polar or nonpolar?

11.64 1,1-dichloroethylene ($CH_2{=}CCl_2$) is a starting material used to prepare the plastic packaging material Saran wrap. Your friend thinks that 1,1-dichloroethylene is a nonpolar molecule because the dipoles in the two C—Cl bonds cancel. Draw out the proper three-dimensional structure of 1,1-dichloroethylene, and then explain why your friend is correct or incorrect.

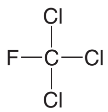
11.65 Indicate the polar bonds in each molecule. Label the bonds with δ^+ and δ^-.

a. $CH_3CH_2OCH_2CH_3$

diethyl ether
(general anesthetic)

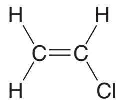
c. 

glycerol
(used in cosmetics)

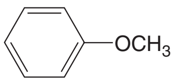
b. 

trichlorofluoromethane
(responsible for atmospheric
ozone destruction)

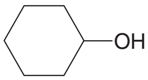
11.66 Indicate the polar bonds in each molecule. Label the bonds with δ^+ and δ^-.

a. 

vinyl chloride

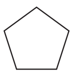
c. 

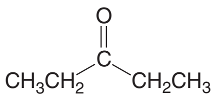
anisole

b. 

cyclohexanol

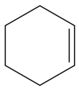
11.67 Classify each molecule as polar or nonpolar.

a. 

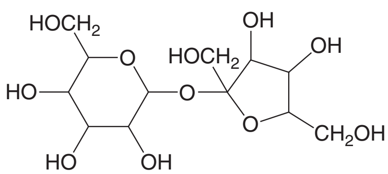
b. 

c. CH_2Br_2

11.68 Classify each molecule as polar or nonpolar.

a. $CH_3OCH_2CH_3$ b. $(CH_3CH_2)_2NH$ c. 

11.69 Sucrose (table sugar) and 1-dodecanol [$(CH_3(CH_2)_{11}OH$] both contain 12 carbon atoms and hydroxyl groups. Explain why sucrose is water soluble, but 1-dodecanol is not water soluble.



sucrose

11.70 Acetic acid (CH_3CO_2H) and palmitic acid [$CH_3(CH_2)_{14}CO_2H$] are both carboxylic acids. Acetic acid is the water-soluble carboxylic acid in vinegar, while palmitic acid is a water-insoluble fatty acid. Give a reason for this solubility difference.

11.71 Spermaceti wax [$CH_3(CH_2)_{14}CO_2(CH_2)_{15}CH_3$], a compound isolated from sperm whales, was once a common ingredient in cosmetics. Its use is now banned to help protect whales. (a) Identify the functional group in spermaceti wax. (b) Predict its solubility properties in water and organic solvents and explain your reasoning.

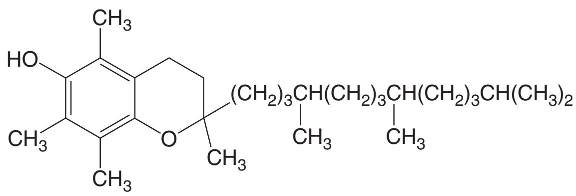
11.72 Beeswax has the structure $CH_3(CH_2)_{14}CO_2(CH_2)_{29}CH_3$. Consider its solubility in three different solvents—water, hexane [$CH_3(CH_2)_4CH_3$], and ethanol (CH_3CH_2OH). In which solvent is beeswax most soluble? In which solvent is beeswax least soluble? Explain your choices.

Vitamins

11.73 Explain why regularly taking a large excess of a fat-soluble vitamin can lead to severe health problems, whereas taking a large excess of a water-soluble vitamin often causes no major health problems.

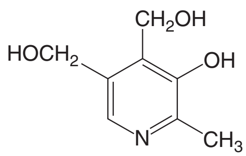
11.74 You can obtain the minimum daily requirement of vitamin E by eating leafy greens or by taking vitamin E tablets. As a source of vitamin E, which of these methods is better for an individual?

11.75 Vitamin E is a natural antioxidant found in fish oil, almonds, hazelnuts, and leafy greens. Predict the solubility of vitamin E in water and in organic solvents.



vitamin E

11.76 Vitamin B_6 is obtained by eating a diet that includes meat, fish, wheat germ, and bananas. A deficiency of vitamin B_6 can cause convulsions and anemia. Predict the solubility of vitamin B_6 in water and in organic solvents.



vitamin B_6
pyridoxine

General Questions

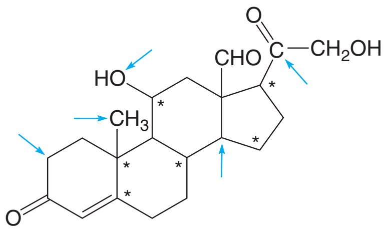
11.77 Can a hydrocarbon have each of the following molecular formulas? Explain why or why not in each case. (a) C_3H_8; (b) C_3H_9; (c) C_3H_6.

11.78 Can an oxygen-containing organic compound have molecular formula C_2H_6O? Explain your reasoning.

11.79 (a) Draw a condensed structure for an amine having molecular formula $C_4H_{11}N$. (b) Label all polar bonds using the symbols δ^+ and δ^-. (c) Determine the geometry around the N atom. (d) Is the compound you drew polar or nonpolar?

11.80 (a) Draw a condensed structure for an alcohol having molecular formula $C_4H_{10}O$. (b) Label all polar bonds using the symbols δ^+ and δ^-. (c) Determine the geometry around the O atom. (d) Is the compound you drew polar or nonpolar?

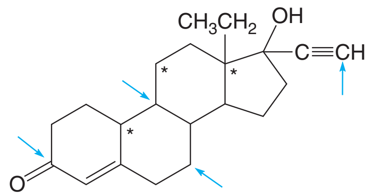
11.81 Answer the following questions about aldosterone, a compound that helps to control the absorption of Na^+ and Cl^- ions in the kidneys, and as a result, affects water retention.



aldosterone

a. Identify the functional groups.
b. Draw in all lone pairs on O atoms.
c. How many C's does aldosterone contain?
d. How many H's are present at each C labeled with an asterisk (*)?
e. Give the shape around each atom indicated with an arrow.
f. Label all polar bonds.

11.82 Answer the following questions about levonorgestrel (trade name: Plan B). Levonorgestrel interferes with ovulation, the release of an egg from an ovary, so it prevents pregnancy if taken within a few days of unprotected sex.



levonorgestrel

a. Identify the functional groups.
b. How many C's does levonorgestrel contain?
c. How many H's are present at each C labeled with an asterisk (*)?
d. Give the shape around each atom indicated with an arrow.
e. Label all polar bonds.
f. Is levonorgestrel soluble in an organic solvent?
g. Is levonorgestrel soluble in water?

Applications

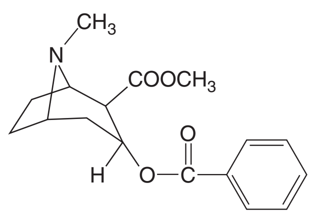
11.83 Cabbage leaves are coated with a hydrocarbon of molecular formula $C_{29}H_{60}$. What purpose might this hydrocarbon coating serve?

11.84 Skin moisturizers come in two types. (a) One type of moisturizer is composed mainly of hydrocarbon material. Suggest a reason as to how a moisturizer of this sort helps to keep the skin from drying out. (b) A second type of moisturizer is composed mainly of propylene glycol [$CH_3CH(OH)CH_2OH$]. Suggest a reason as to how a moisturizer of this sort helps to keep the skin from drying out.

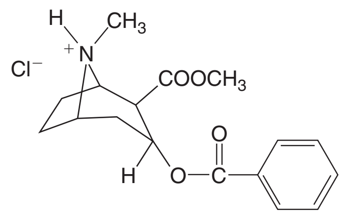
CHALLENGE QUESTIONS

11.85 THC is the active component in marijuana (Section 11.5), and ethanol (CH_3CH_2OH) is the alcohol in alcoholic beverages. Using the solubility principles in Section 11.6, predict the water solubility of each of these compounds. Then, explain why drug screenings are able to detect the presence of THC but not ethanol weeks after these substances have been introduced into the body.

11.86 Cocaine is a widely abused, addicting drug. Cocaine is usually obtained as its hydrochloride salt (cocaine hydrochloride, an ionic salt). This salt can be converted to crack (a neutral molecule) by treatment with base.



cocaine (crack)
neutral organic molecule



cocaine hydrochloride
a salt

a. Identify the functional groups in cocaine.
b. Given what you have learned about ionic and covalent bonding, which of the two compounds—crack or cocaine hydrochloride—has a higher boiling point?
c. Which compound is more soluble in water?
d. Can you use the relative solubility to explain why crack is usually smoked but cocaine hydrochloride is injected directly into the bloodstream?

12

CHAPTER OUTLINE

CHAPTER GOALS

In this chapter you will learn how to:

1. Identify and draw acyclic alkanes and cycloalkanes
2. Identify constitutional isomers
3. Name alkanes using the IUPAC system of nomenclature
4. Predict the physical properties of alkanes
5. Write equations for the complete and incomplete combustion of alkanes



Petroleum is a complex mixture of compounds that includes hydrocarbons such as hexane and decane, two members of the family of organic compounds called **alkanes.**

ALKANES

IN Chapter 12, we apply the principles of bonding, shape, and physical properties discussed in Chapter 11 to our first family of organic compounds, the **alkanes.** Since alkanes have no functional group, their chemical reactions are limited, and much of Chapter 12 is devoted to learning how to name and draw them. Alkanes do, however, undergo one important reaction, combustion, a process that powers automobiles and heats homes. The combustion of alkanes has also increased the carbon dioxide concentration in the atmosphere over the last 50 years, which may have long-term and far-reaching environmental consequences.

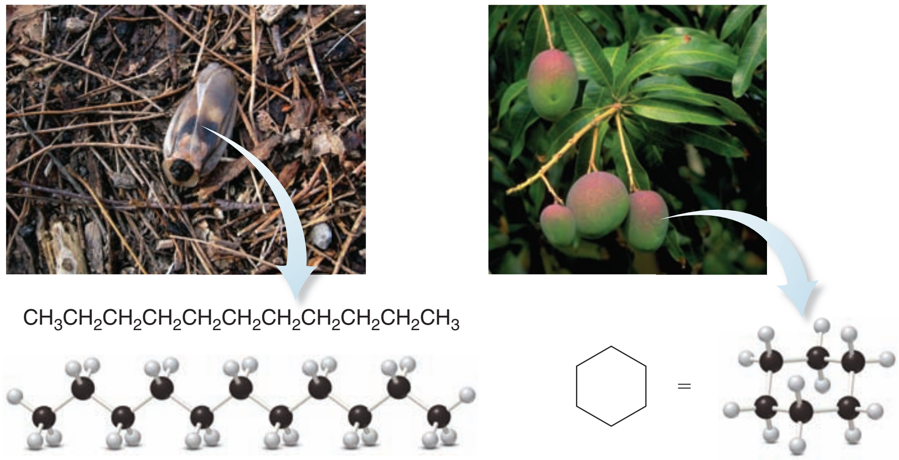
12.1 INTRODUCTION

***Alkanes* are hydrocarbons having only C—C and C—H single bonds.** The carbons of an alkane can be joined together to form chains or rings of atoms.

The prefix *a-* means *not,* so an acyclic alkane is *not* cyclic.

- **Alkanes that contain chains of carbon atoms but no rings are called *acyclic alkanes.*** An acyclic alkane has the molecular formula $\mathbf{C_nH_{2n+2}}$, where *n* is the number of carbons it contains. Acyclic alkanes are also called **saturated hydrocarbons** because they have the maximum number of hydrogen atoms per carbon.
- ***Cycloalkanes* contain carbons joined in one or more rings.** Since a cycloalkane has two fewer H's than an acyclic alkane with the same number of carbons, its general formula is $\mathbf{C_nH_{2n}}$.

Undecane and cyclohexane are examples of two naturally occurring alkanes. Undecane is an acyclic alkane with molecular formula $C_{11}H_{24}$. Undecane is a ***pheromone*, a chemical substance used for communication** in a specific animal species, most commonly an insect population. Secretion of undecane by a cockroach causes other members of the species to aggregate. Cyclohexane, a cycloalkane with molecular formula C_6H_{12}, is one component of the mango, the most widely consumed fruit in the world.



undecane

cyclohexane

PROBLEM 12.1 How many hydrogen atoms are present in each compound?

a. an acyclic alkane with three carbons
b. a cycloalkane with four carbons
c. a cycloalkane with nine carbons
d. an acyclic alkane with seven carbons

PROBLEM 12.2 Which formulas represent acyclic alkanes and which represent cycloalkanes?

a. C_5H_{12} b. C_4H_8 c. $C_{12}H_{24}$ d. $C_{10}H_{22}$

12.2 SIMPLE ALKANES

We begin our study of alkanes with acyclic alkanes, and then move on to cycloalkanes in Section 12.5.

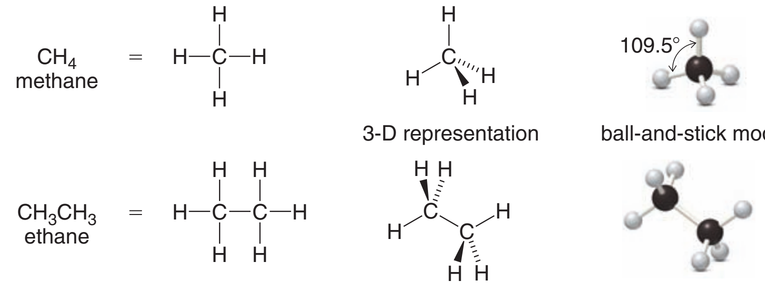
12.2A ACYCLIC ALKANES HAVING FEWER THAN FIVE CARBONS

The structures for the two simplest acyclic alkanes were given in Chapter 11.

- **Methane, $\mathbf{CH_4}$,** has a single carbon atom surrounded by four hydrogens to give it four bonds.
- **Ethane, $\mathbf{CH_3CH_3}$,** has two carbon atoms joined together by a single bond. Each carbon is also bonded to three hydrogens to give it four bonds total.

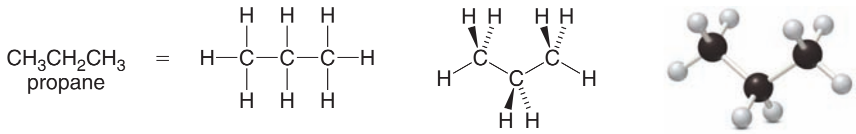
To draw the structure of an alkane, join the carbon atoms together with single bonds, and add enough H's to give each C four bonds.

Since each carbon in an alkane is surrounded by four atoms, each carbon is **tetrahedral,** and all bond angles are 109.5°.



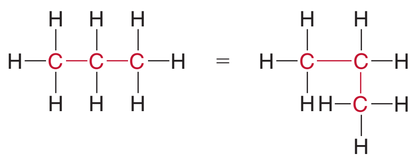
3-D representation ball-and-stick model

To draw a three-carbon alkane, draw three carbons joined together with single bonds and add enough hydrogens to give each carbon four bonds. This forms **propane, $CH_3CH_2CH_3$.**



3-D representation ball-and-stick model

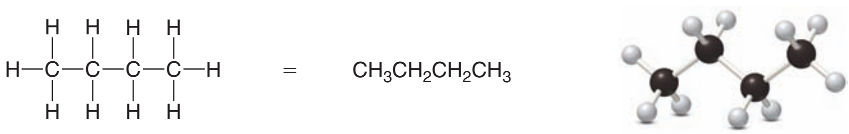
The carbon skeleton in propane and other alkanes can be drawn in a variety of different ways and still represent the same molecule. For example, the three carbons of propane can be drawn in a horizontal row or with a bend. *These representations are equivalent.* **If you follow the carbon chain from one end to the other, you move across the *same* three carbon atoms in both representations.**


3 C's in a row 3 C's with a bend

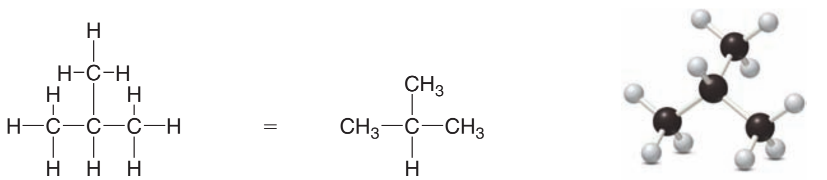
- **The bends in a carbon chain don't matter when it comes to identifying different compounds.**

There are two different ways to arrange four carbons, giving two compounds with molecular formula C_4H_{10}.

- **Butane, $CH_3CH_2CH_2CH_3$,** has four carbon atoms in a row. Butane is a **straight-chain alkane,** an alkane that has all of its carbons in one continuous chain.
- **Isobutane, $(CH_3)_3CH$,** has three carbon atoms in a row and one carbon bonded to the middle carbon. Isobutane is a **branched-chain alkane,** an alkane that contains one or more carbon branches bonded to a carbon chain.



butane 4 C's in a row **straight-chain alkane**

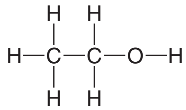


isobutane 3 C's with a one-carbon branch **branched-chain alkane**

Butane and isobutane are ***isomers,*** **two different compounds with the same molecular formula.** They belong to one of the two major classes of isomers called **constitutional isomers.**

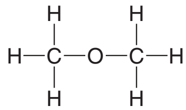
- *Constitutional isomers* differ in the way the atoms are connected to each other.

Constitutional isomers like butane and isobutane belong to the same family of compounds: they are both **alkanes.** This is not always the case. For example, there are two different arrangements of atoms for a compound of molecular formula C_2H_6O.



CH_3CH_2OH

ethanol



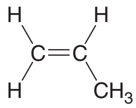
CH_3OCH_3

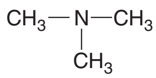
dimethyl ether

Ethanol (CH_3CH_2OH) and dimethyl ether (CH_3OCH_3) are constitutional isomers with different functional groups: CH_3CH_2OH is an **alcohol** and CH_3OCH_3 is an **ether.**

SAMPLE PROBLEM 12.1

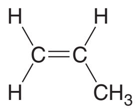
Are the compounds in each pair constitutional isomers or are they not isomers of each other?

a. $CH_3CH_2CH_3$ and 

b. $CH_3CH_2CH_2NH_2$ and 

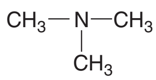
ANALYSIS First compare molecular formulas; two compounds are isomers only if they have the same molecular formula. Then, check how the atoms are connected to each other. Constitutional isomers have atoms bonded to different atoms.

SOLUTION

a. $CH_3CH_2CH_3$ and 

molecular formula C_3H_8 — molecular formula C_3H_6

The two compounds have the same number of C's but a different number of H's, so they have different molecular formulas. Thus, they are *not* isomers of each other.

b. $CH_3CH_2CH_2NH_2$ and 

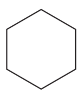
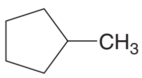
Both compounds have molecular formula C_3H_9N. Since one compound has C–C bonds and the other does not, the atoms are connected differently. These compounds are *constitutional isomers.*

PROBLEM 12.3

Are the compounds in each pair isomers or are they not isomers of each other?

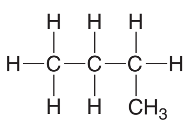
a. $CH_3CH_2CH_2CH_3$ and $CH_3CH_2CH_3$

b. $CH_3CH_2CH_2OH$ and $CH_3OCH_2CH_3$

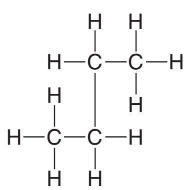
c.  and 

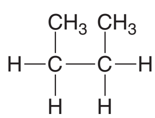
PROBLEM 12.4

Label each representation as butane or isobutane.

a. 

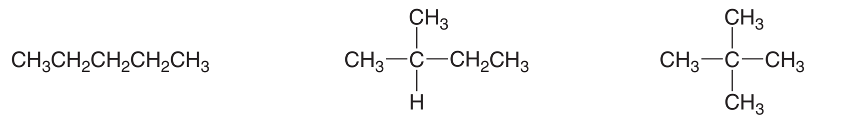
b. $HC(CH_3)_3$

c. 

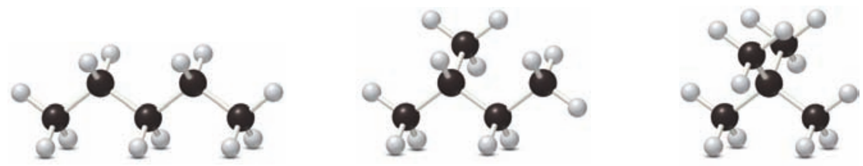
d. 

12.2B ACYCLIC ALKANES HAVING FIVE OR MORE CARBONS

As the number of carbon atoms in an alkane increases, so does the number of isomers. There are three constitutional isomers for the five-carbon alkane, each having molecular formula C_5H_{12}: **pentane, isopentane** (or 2-methylbutane), and **neopentane** (or 2,2-dimethylpropane).



pentane — isopentane (2-methylbutane) — neopentane (2,2-dimethylpropane)



With alkanes having five or more carbons, the names of the straight-chain isomers are derived from Greek roots: ***pent***ane for **five** carbons, ***hex***ane for **six,** and so on. Table 12.1 lists the names and structures for the straight-chain alkanes having up to 10 carbons. The suffix ***-ane*** identifies a molecule as an alk***ane.*** The remainder of the name—meth-, eth-, prop-, and so forth—indicates the number of carbons in the long chain.

The suffix ***-ane*** identifies a molecule as an alk***ane.***

TABLE 12.1 Straight-Chain Alkanes

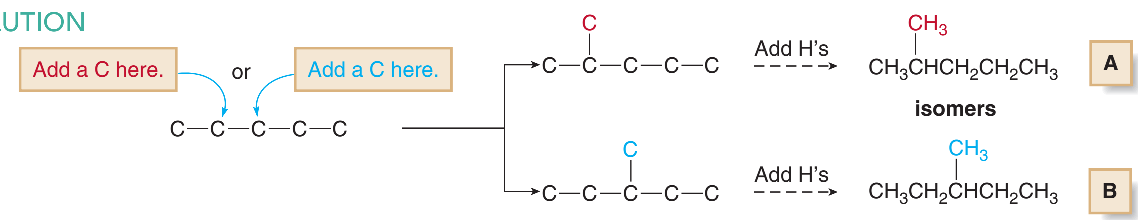
Number of C's	Molecular Formula	Structure	Name
1	CH_4	CH_4	*meth*ane
2	C_2H_6	CH_3CH_3	*eth*ane
3	C_3H_8	$CH_3CH_2CH_3$	*prop*ane
4	C_4H_{10}	$CH_3CH_2CH_2CH_3$	*but*ane
5	C_5H_{12}	$CH_3CH_2CH_2CH_2CH_3$	*pent*ane
6	C_6H_{14}	$CH_3CH_2CH_2CH_2CH_2CH_3$	*hex*ane
7	C_7H_{16}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_3$	*hept*ane
8	C_8H_{18}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_3$	*oct*ane
9	C_9H_{20}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_3$	*non*ane
10	$C_{10}H_{22}$	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_3$	*dec*ane

SAMPLE PROBLEM 12.2

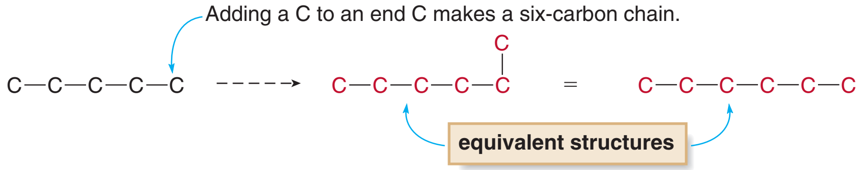
Draw two isomers with molecular formula C_6H_{14} that have five carbon atoms in the longest chain and a one-carbon branch coming off the chain.

ANALYSIS Since isomers are different compounds with the same molecular formula, we must add a one-carbon branch to two different carbons to form two different products. Then add enough H's to give each C four bonds.

SOLUTION

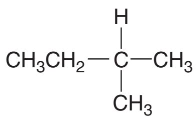


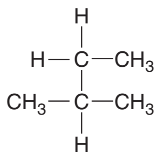
Compounds **A** and **B** are isomers because the CH_3 group is bonded to different atoms in the five-carbon chain. Note, too, that we cannot add the one-carbon branch to an *end* carbon because that creates a continuous six-carbon chain. Remember that **bends in the chain don't matter.**



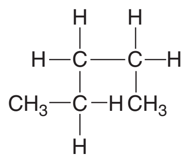
PROBLEM 12.5 Draw two isomers with molecular formula C_6H_{14} that have four carbon atoms in the longest chain and two one-carbon branches coming off the chain.

PROBLEM 12.6 Which of the following is *not* another representation for isopentane?

a. 

b. 

c. $CH_3CH_2CH(CH_3)_2$

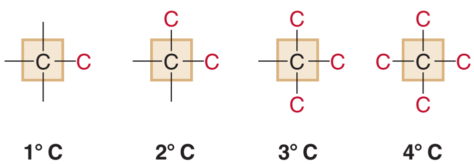
d. 

12.2C CLASSIFYING CARBON ATOMS

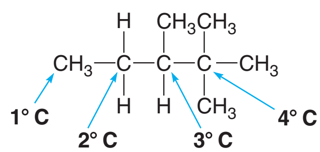
Carbon atoms in alkanes and other organic compounds are classified by the number of other carbons directly bonded to them.

- A *primary carbon* (1° C) is bonded to *one* other C.
- A *secondary carbon* (2° C) is bonded to *two* other C's.
- A *tertiary carbon* (3° C) is bonded to *three* other C's.
- A *quaternary carbon* (4° C) is bonded to *four* other C's.

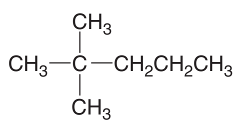
Classification of carbon atoms



Example

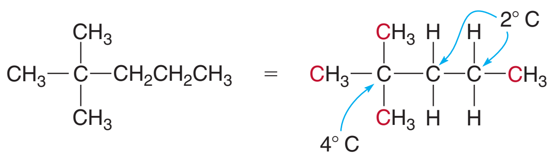


SAMPLE PROBLEM 12.3 Classify each carbon atom in the following molecule as 1°, 2°, 3°, or 4°.



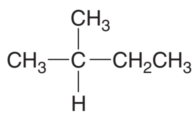
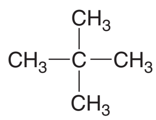
ANALYSIS To classify a carbon atom, count the number of C's bonded to it. Draw a complete structure with all bonds and atoms to clarify the structure if necessary.

SOLUTION



All C's labeled in red are 1° C's.

PROBLEM 12.7 Classify the carbon atoms in each compound as 1°, 2°, 3°, or 4°.

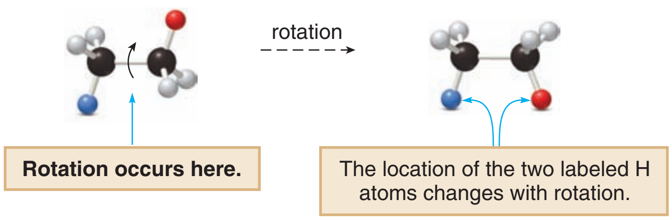
a. $CH_3CH_2CH_2CH_3$ b. $(CH_3)_3CH$ c.  d. 

PROBLEM 12.8 Draw a condensed structure for an alkane that fits each description.

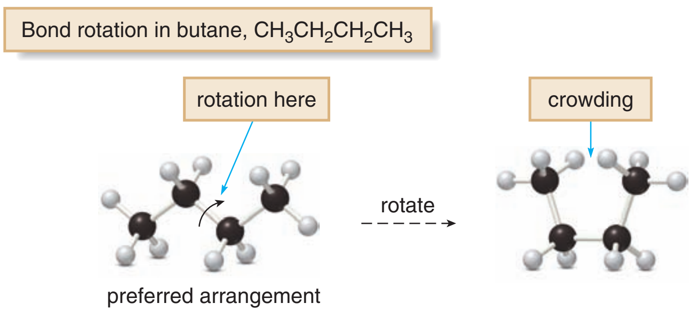
a. an alkane that contains only 1° and 2° carbons
b. an alkane of molecular formula C_5H_{12} that has one 3° carbon
c. an alkane with two 4° carbons

12.2D BOND ROTATION AND SKELETAL STRUCTURES FOR ACYCLIC ALKANES

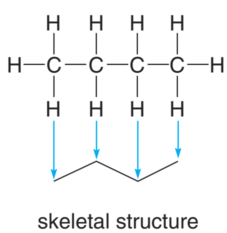
A ball-and-stick model of ethane with two labeled hydrogens reveals an important feature. **Rotation can occur around carbon–carbon single bonds.** This allows the hydrogens on one CH_3 group to adopt different orientations relative to the hydrogens on the other CH_3 group. This is a characteristic of *all* carbon–carbon single bonds.



In a similar fashion, each carbon–carbon bond in butane ($CH_3CH_2CH_2CH_3$) undergoes rotation, a process that is rapid at room temperature. As a result, the carbon backbone of butane can be arranged in a variety of ways. The most stable arrangement avoids crowding between nearby carbons, so that the carbon skeleton is extended in a zigzag fashion.

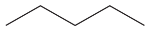


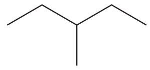
Sometimes zigzag skeletal structures are used to represent these extended carbon skeletons. Recall from Section 11.4 that a skeletal structure has a carbon atom at the intersection of any two lines and at the end of each line. Each carbon has enough hydrogens to give it four bonds.

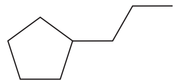


PROBLEM 12.9 Draw a skeletal structure for each compound: (a) $CH_3CH_2CH_2CH_2CH_2CH_3$ (hexane); (b) $CH_3(CH_2)_5CH_3$ (heptane).

PROBLEM 12.10 Convert each skeletal structure to a complete structure with all atoms and bond lines.

a. 

b. 

c. 

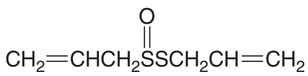
12.3 AN INTRODUCTION TO NOMENCLATURE

12.3A THE IUPAC SYSTEM OF NOMENCLATURE

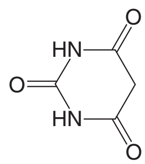
How are organic compounds named? Long ago, the name of a compound was often based on the plant or animal source from which it was obtained. For example, the name allicin, the principal component of the odor of garlic, is derived from the botanical name for garlic, *Allium sativum.* Other compounds were named by their discoverer for more personal reasons. Adolf von Baeyer supposedly named barbituric acid after a woman named Barbara, although no one knows Barbara's identity—a lover, a Munich waitress, or even St. Barbara.



Garlic has been used in Chinese herbal medicine for over 4,000 years. Today it is sold as a dietary supplement because of its reported health benefits. **Allicin,** the molecule responsible for garlic's odor, is not stored in the garlic bulb, but rather is produced by the action of enzymes when the bulb is crushed or bruised.



allicin
(odor of garlic)



barbituric acid
(named for Barbara whom?)

With the isolation and preparation of thousands of new organic compounds it became obvious that each organic compound must have an unambiguous name. A systematic method of naming compounds (a system of **nomenclature**) was developed by the ***I***nternational ***U***nion of ***P***ure and ***A***pplied ***C***hemistry. It is referred to as the **IUPAC** system of nomenclature, and how it can be used to name alkanes is explained in Section 12.4.

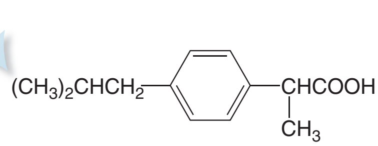
12.3B FOCUS ON HEALTH & MEDICINE NAMING NEW DRUGS

Naming organic compounds has become big business for drug companies. The IUPAC name of an organic compound can be long and complex. As a result, most drugs have three names:

- **Systematic: The systematic name follows the accepted rules of nomenclature; this is the IUPAC name.**
- **Generic: The generic name is the official, internationally approved name for the drug.**
- **Trade: The trade name for a drug is assigned by the company that manufactures it. Trade names are often "catchy" and easy to remember. Companies hope that the public will continue to purchase a drug with an easily recalled trade name long after a cheaper generic version becomes available.**

Consider the world of over-the-counter anti-inflammatory agents. The compound a chemist calls 2-[4-(2-methylpropyl)phenyl]propanoic acid has the generic name ibuprofen. It is marketed under a variety of trade names, including Motrin and Advil.



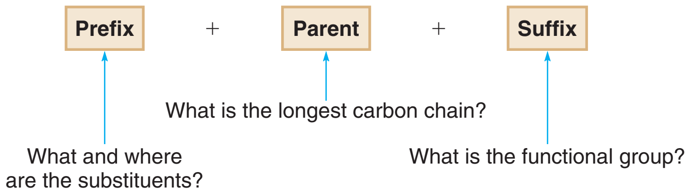


Systematic name: 2-[4-(2-methylpropyl)phenyl]propanoic acid
Generic name: ibuprofen
Trade name: Motrin or Advil

12.4 ALKANE NOMENCLATURE

Although the names of the straight-chain alkanes having 10 carbons or fewer were already given in Table 12.1, we must also learn how to name alkanes that have carbon branches, called **substituents,** bonded to a long chain. The names of these organic molecules have three parts.

- The **parent name** indicates the number of carbons in the longest continuous carbon chain in the molecule.
- The **suffix** indicates what functional group is present.
- The **prefix** tells us the identity, location, and number of substituents attached to the carbon chain.



The names of the straight-chain alkanes in Table 12.1 consist of two parts. The suffix *-ane* indicates that the compounds are alkanes. The remainder of the name is the parent name, which indicates the number of carbon atoms in the longest carbon chain. The parent name for **one carbon is *meth-*,** for **two carbons is *eth-*,** and so on. Thus, we are already familiar with two parts of the name of an organic compound.

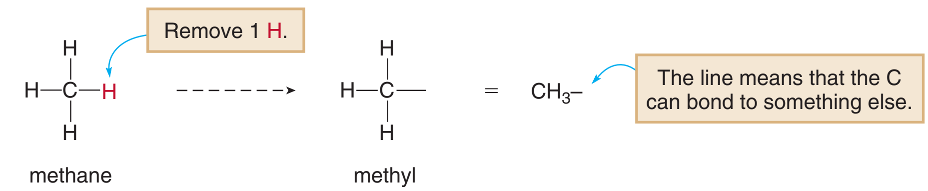
To determine the third part of a name, the prefix, we must learn how to name the substituents that are bonded to the longest carbon chain.

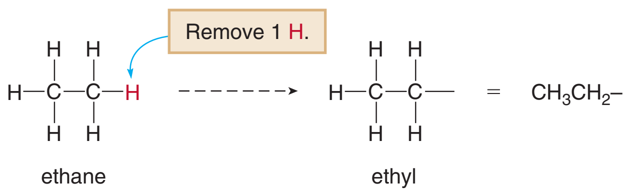
12.4A NAMING SUBSTITUENTS

Carbon substituents bonded to a long carbon chain are called *alkyl groups.*

- An *alkyl group* is formed by removing one hydrogen from an alkane.

An alkyl group is a part of a molecule that is now able to bond to another atom or a functional group. **To name an alkyl group, change the *-ane* ending of the parent alkane to *-yl.*** Thus, methane (CH_4) becomes methyl (CH_3–) and ethane (CH_3CH_3) becomes ethyl (CH_3CH_2–).





Removing one hydrogen from an *end* carbon in any straight-chain alkane forms other alkyl groups named in a similar fashion. Thus, propane ($CH_3CH_2CH_3$) becomes propyl ($CH_3CH_2CH_2$–) and butane ($CH_3CH_2CH_2CH_3$) becomes butyl ($CH_3CH_2CH_2CH_2$–). The names of alkyl groups having six carbons or fewer are summarized in Table 12.2.

TABLE 12.2 Some Common Alkyl Groups

Number of C's	Structure	Name
1	CH_3–	methyl
2	CH_3CH_2–	ethyl
3	$CH_3CH_2CH_2$–	propyl
4	$CH_3CH_2CH_2CH_2$–	butyl
5	$CH_3CH_2CH_2CH_2CH_2$–	pentyl
6	$CH_3CH_2CH_2CH_2CH_2CH_2$–	hexyl

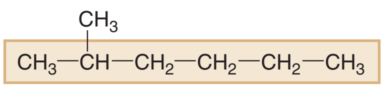
12.4B NAMING AN ACYCLIC ALKANE

Four steps are needed to name an alkane.

HOW TO Name an Alkane Using the IUPAC System

Step [1] Find the parent carbon chain and add the suffix.

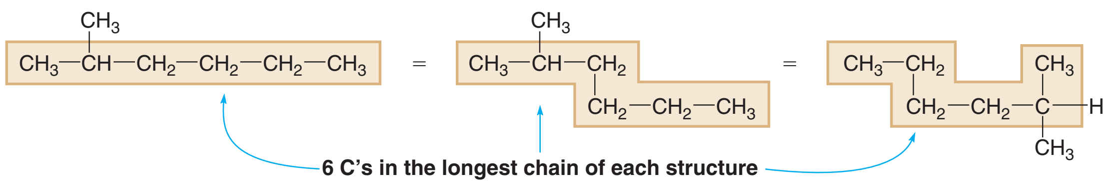
- **Find the longest continuous carbon chain,** and name the molecule using the parent name for that number of carbons, given in Table 12.1. To the name of the parent, add the suffix ***-ane*** for an alkane. Each functional group has its own suffix.



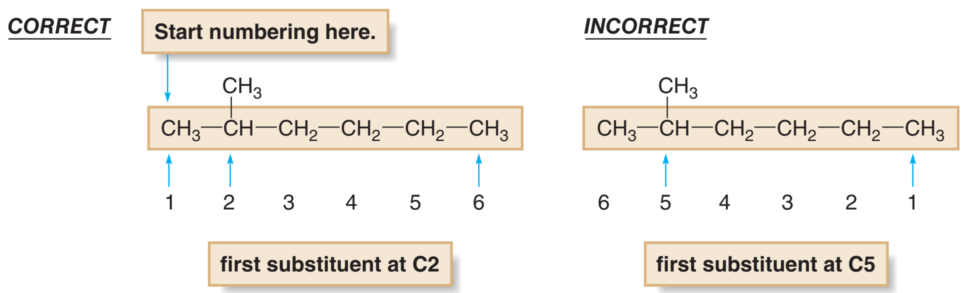
6 C's in the longest chain

6 C's ----> **hexane**

- The longest chain may not be written horizontally across the page. Remember that **it does not matter if the chain is *straight* or has *bends*.** All of the following representations are equivalent.

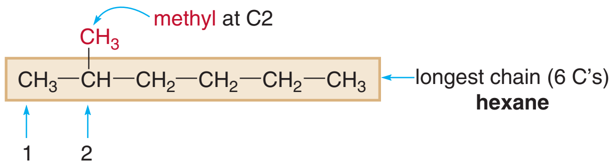


Step [2] Number the atoms in the carbon chain to give the first substituent the lower number.

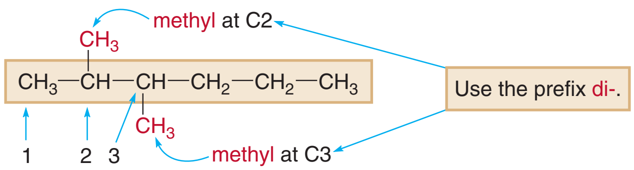


Step [3] Name and number the substituents.

- Name the substituents as alkyl groups, and use the numbers from step [2] to designate their location.



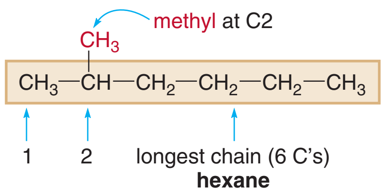
- Every carbon belongs to *either* the longest chain or a substituent, but *not both.*
- Each substituent needs its *own* number.
- If two or more identical substituents are bonded to the longest chain, use **prefixes** to indicate how many: **di-** for two groups, **tri-** for three groups, **tetra-** for four groups, and so forth. The following compound has two methyl groups so its name contains the prefix di- before methyl → *di*methyl.



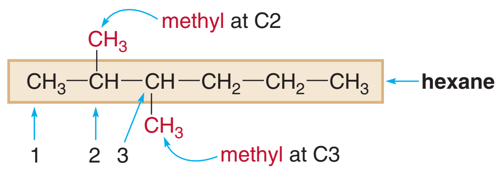
Step [4] Combine substituent names and numbers + parent + suffix.

- Precede the name of the parent by the names of the substituents. **Alphabetize** the names of the substituents, ignoring any prefixes like *di-*. For example, triethyl precedes dimethyl because the *e* of **e**thyl comes before the *m* of **m**ethyl in the alphabet.
- Precede the name of each substituent by the number that indicates its location. There must be ***one number for each substituent.***
- Separate numbers by commas and separate numbers from letters by dashes.

To help identify which carbons belong to the longest chain and which are substituents, always box in the atoms of the long chain. Every other carbon atom then becomes a substituent that needs its own name as an alkyl group.



Answer: 2-methylhexane

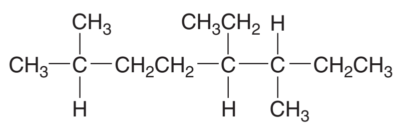


- Two numbers are needed, one for each methyl group.

Answer: 2,3-dimethylhexane

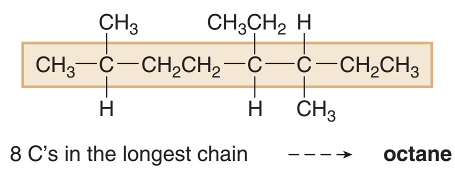
SAMPLE PROBLEM 12.4

Give the IUPAC name for the following compound.



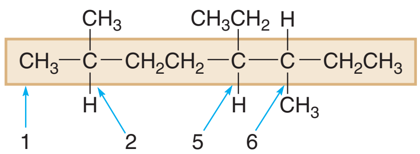
ANALYSIS AND SOLUTION

[1] **Name the parent and use the suffix *-ane* since the molecule is an alkane.**



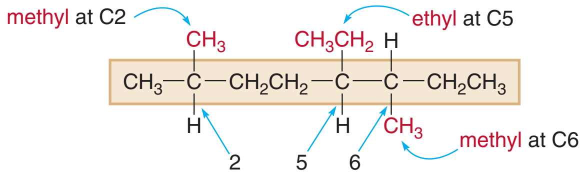
- Box in the atoms of the longest chain to clearly show which carbons are part of the longest chain and which carbons are substituents.

[2] **Number the chain to give the first substituent the lower number.**



- Numbering from left to right puts the first substituent at C2.

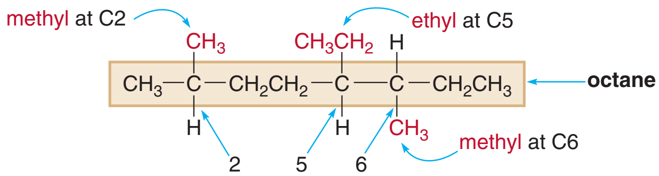
[3] **Name and number the substituents.**



- This compound has three substituents: two methyl groups at C2 and C6 and an ethyl group at C5.

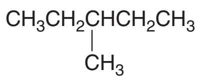
[4] **Combine the parts.**

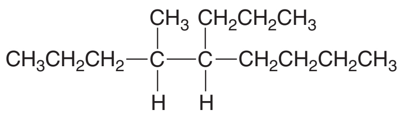
- Write the name as one word and use the prefix di- before methyl since there are two methyl groups.
- Alphabetize the *e* of **e**thyl before the *m* of **m**ethyl. The prefix di- is ignored when alphabetizing.

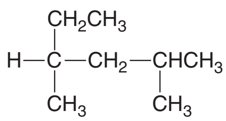


Answer: 5-ethyl-2,6-dimethyloctane

PROBLEM 12.11 Give the IUPAC name for each compound.

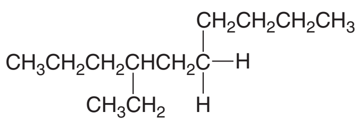
a. 

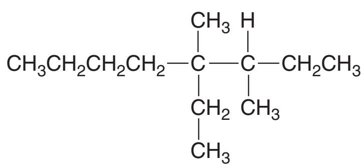
b. 

c. 

PROBLEM 12.12 Give the IUPAC name for each compound.

a. $(CH_3)_2CHCH(CH_3)_2$

b. 

c. 

You must also know how to derive a structure from a given name. Sample Problem 12.5 demonstrates a stepwise method.

SAMPLE PROBLEM 12.5

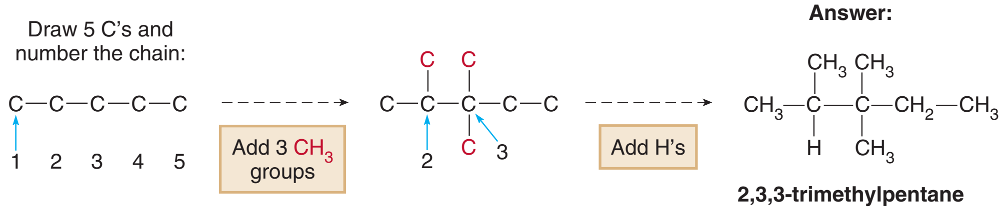
Give the structure with the following IUPAC name: 2,3,3-trimethylpentane.

ANALYSIS

To derive a structure from a name, first look at the end of the name to find the parent name and suffix. From the parent we know the number of C's in the longest chain, and the suffix tells us the functional group; the suffix -ane = an alkane. Then, number the carbon chain from either end and add the substituents. Finally, add enough H's to give each C four bonds.

SOLUTION

2,3,3-Trimethyl**pentane** has **pentane** (5 C's) as the longest chain and three methyl groups at carbons 2, 3, and 3.



PROBLEM 12.13

Give the structure corresponding to each IUPAC name.

a. 3-methylhexane
b. 3,3-dimethylpentane
c. 3,5,5-trimethyloctane
d. 3-ethyl-4-methylhexane

PROBLEM 12.14

Give the structure corresponding to each IUPAC name.

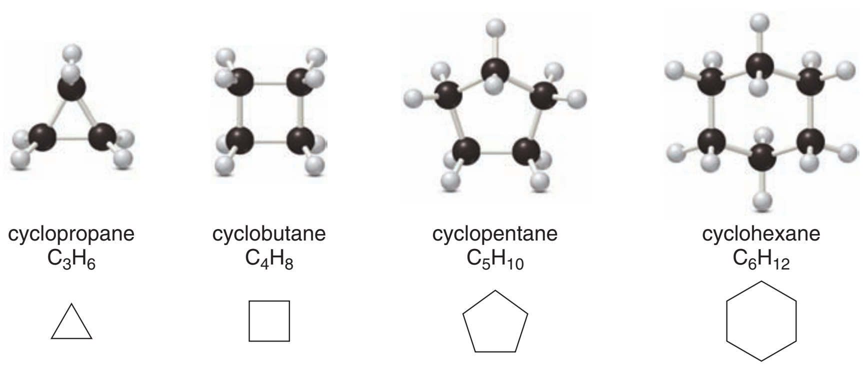
a. 2,2-dimethylbutane
b. 6-butyl-3-methyldecane
c. 4,4,5,5-tetramethylnonane
d. 3-ethyl-5-propylnonane

12.5 CYCLOALKANES

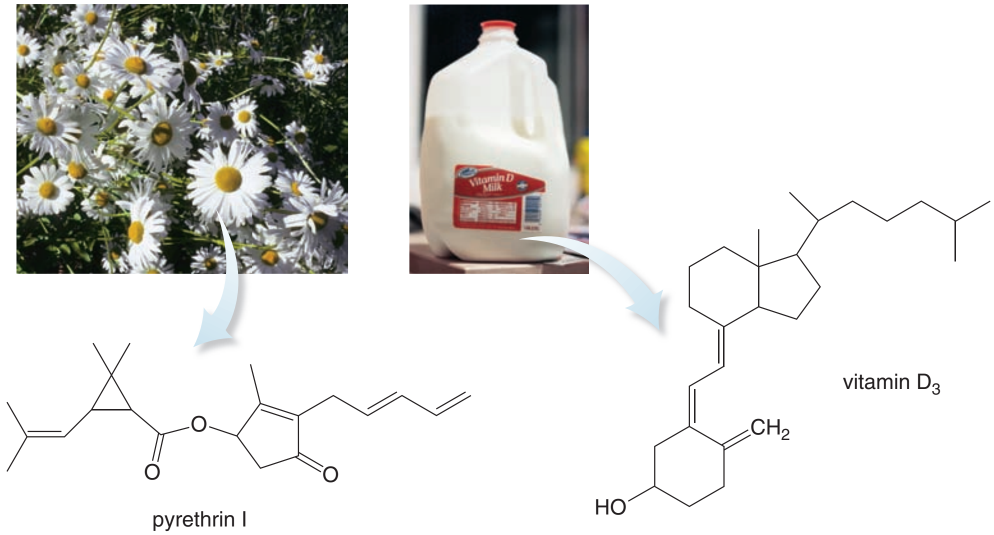
Cycloalkanes contain carbon atoms arranged in a ring. Think of a cycloalkane as being formed by removing two H's from the end carbons of a chain, and then bonding the two carbons together.

12.5A SIMPLE CYCLOALKANES

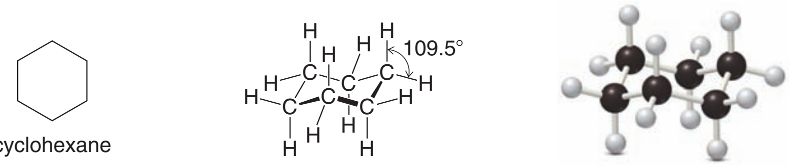
Simple cycloalkanes are named by adding the prefix *cyclo-* to the name of the acyclic alkane having the same number of carbons. Cycloalkanes having three to six carbon atoms are shown in the accompanying figure. They are drawn using polygons in skeletal representations (Section 11.4). Each corner of the polygon has a carbon atom with two hydrogen atoms to give it four bonds.



Cyclic compounds occur widely in nature and many have interesting and important biological properties. For example, **pyrethrin I,** a naturally occurring insecticide obtained from chrysanthemums, contains both a three- and five-membered ring. **Vitamin D_3,** a fat-soluble vitamin that regulates calcium and phosphorus metabolism, contains six- and five-membered rings. Many foods, particularly milk, are fortified with vitamin D_3 so that we get enough of this vital nutrient in our diet.



Although we draw cycloalkanes as flat polygons, in reality cycloalkanes with more than three carbons are not planar molecules. Cyclohexane, for example, adopts a puckered arrangement called the **chair** form, in which all bond angles are 109.5°.



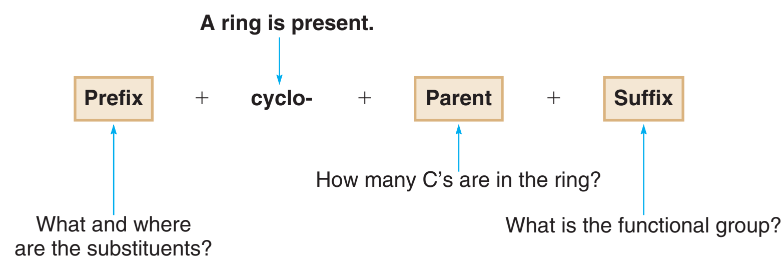
skeletal structure | nonplanar cyclohexane **chair form** | ball-and-stick model

PROBLEM 12.15 Review: Label the functional groups in pyrethrin I.

PROBLEM 12.16 Review: Explain why vitamin D_3 is a fat-soluble vitamin.

12.5B NAMING CYCLOALKANES

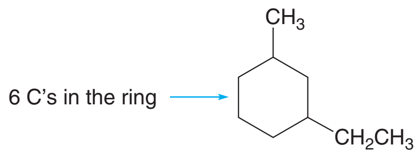
Cycloalkanes are named using the rules in Section 12.4, but the prefix *cyclo-* immediately precedes the name of the parent.



HOW TO Name a Cycloalkane Using the IUPAC System

Step [1] Find the parent cycloalkane.

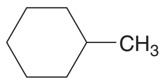
- Count the number of carbon atoms in the ring and use the parent name for that number of carbons. Add the prefix *cyclo-* and the suffix *-ane* to the parent name.



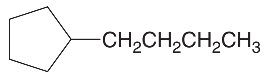
cyclohexane

Step [2] Name and number the substituents.

- No number is needed to indicate the location of a **single** substituent.

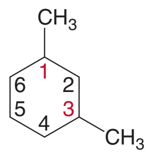


methylcyclohexane



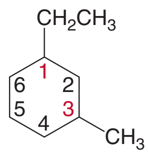
butylcyclopentane

- For rings with more than one substituent, begin numbering at one substituent, and then give the **second substituent** the lower number. With two **different** substituents, number the ring to assign the lower number to the substituents **alphabetically.**



• Place CH_3 groups at C1 and C3.

1,3-dimethylcyclohexane
(*not* 1,5-dimethylcyclohexane)



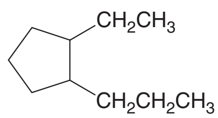
Earlier letter ----> lower number

- **e**thyl group at **C1**
- **m**ethyl group at **C3**

1-ethyl-3-methylcyclohexane
(*not* 3-ethyl-1-methylcyclohexane)

SAMPLE PROBLEM 12.6

Give the IUPAC name for the following compound.

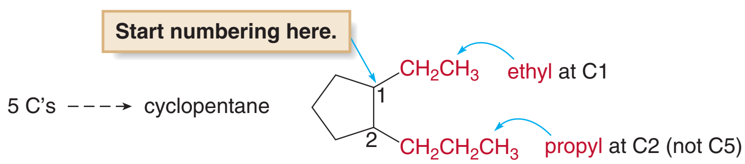


ANALYSIS AND SOLUTION

[1] **Name the ring.** The ring has 5 C's so the molecule is named as a cyclopentane.

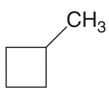
[2] **Name and number the substituents.**

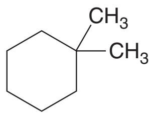
- There are two substituents: CH_3CH_2- is an ethyl group and $CH_3CH_2CH_2-$ is a propyl group.
- Number to put the two groups at C1 and C2 (not C1 and C5).
- Place the ethyl group at C1 since the *e* of ethyl comes before the *p* of propyl in the alphabet.

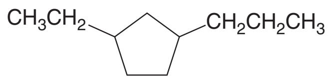


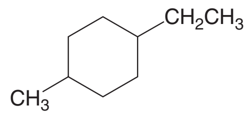
Answer: 1-ethyl-2-propylcyclopentane

PROBLEM 12.17 Give the IUPAC name for each compound.

a. 

b. 

c. 

d. 

PROBLEM 12.18 Give the structure corresponding to each IUPAC name.

a. propylcyclopentane
b. 1,2-dimethylcyclobutane
c. 1,1,2-trimethylcyclopropane
d. 4-ethyl-1,2-dimethylcyclohexane

12.6 FOCUS ON THE ENVIRONMENT FOSSIL FUELS

Many alkanes occur in nature, primarily in natural gas and petroleum. Both of these fossil fuels serve as energy sources, formed long ago by the degradation of organic material.

CONSUMER NOTE

Natural gas is odorless. The smell observed in a gas leak is due to minute amounts of a sulfur additive such as methanethiol, CH_3SH, which provides an odor for easy detection and safety.

Natural gas is composed largely of **methane** (60–80% depending on its source), with lesser amounts of ethane, propane, and butane. These organic compounds burn in the presence of oxygen, releasing energy for cooking and heating (Section 12.8).

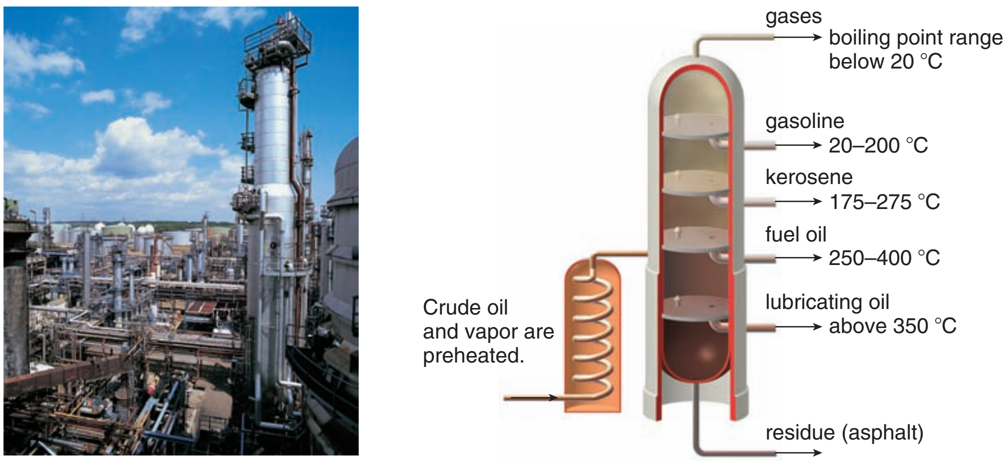
Petroleum is a complex mixture of compounds, most of which are hydrocarbons containing 1–40 carbon atoms. Distilling crude petroleum, a process called **refining,** separates it into usable fractions that differ in boiling point (Figure 12.1). Most products of petroleum refining provide fuel for home heating, automobiles, diesel engines, and airplanes. Each fuel type has a different composition of hydrocarbons, as indicated below.

- **Gasoline:** $C_5H_{12}—C_{12}H_{26}$
- **Kerosene:** $C_{12}H_{26}—C_{16}H_{34}$
- **Diesel fuel:** $C_{15}H_{32}—C_{18}H_{38}$

ENVIRONMENTAL NOTE

Methane is formed and used in a variety of ways. The CH_4 released from decaying vegetable matter in New York City's main landfill is used for heating homes. CH_4 generators in China convert cow manure into energy in rural farming towns.

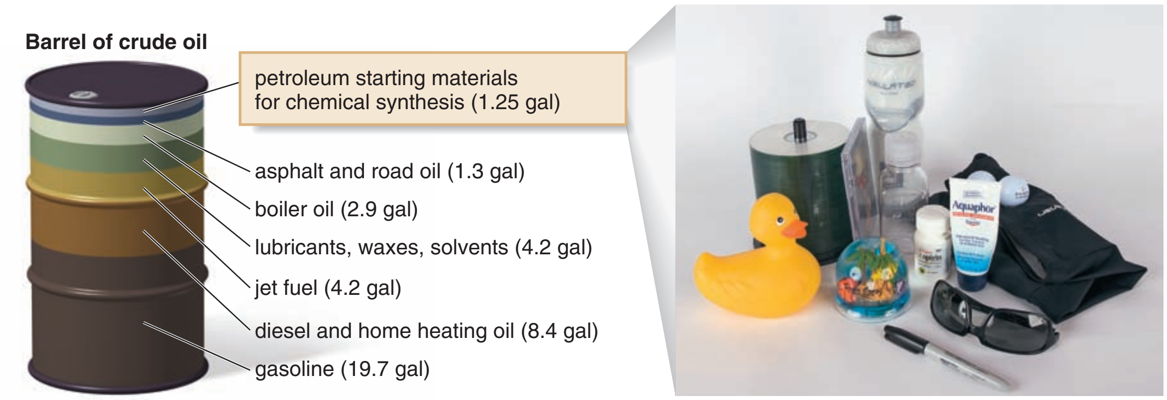
FIGURE 12.1 Refining Crude Petroleum into Usable Fuel and Other Petroleum Products



(a) **An oil refinery.** At an oil refinery, crude petroleum is separated into fractions of similar boiling point.

(b) **A refinery tower.** As crude petroleum is heated, the lower-boiling components come off at the top of the tower, followed by fractions of higher boiling point.

Petroleum provides more than fuel. About 3% of crude oil is used to make plastics and other synthetic compounds, including drugs, fabrics, dyes, and pesticides. These products are responsible for many of the comforts we now take for granted in industrialized countries. Imagine what life would be like without air-conditioning, refrigeration, anesthetics, and pain relievers, all products of the petroleum industry. Consider college students living without CDs and spandex!



products made from petroleum

Energy from petroleum is *nonrenewable,* and the remaining known oil reserves are limited. Given our dependence on petroleum, not only for fuel, but also for the many necessities of modern society, it becomes obvious that we must both conserve what we have and find alternate energy sources.

12.7 PHYSICAL PROPERTIES

Alkanes contain only nonpolar C—C and C—H bonds, so they exhibit only **weak intermolecular forces.** As a result, alkanes have low melting points and boiling points. Low molecular weight alkanes are gases at room temperature, and alkanes used in gasoline are all liquids.

The melting points and boiling points of alkanes increase as the number of carbons increases. Increased surface area increases the force of attraction between molecules, thus raising the boiling point and melting point. This is seen in comparing the boiling points of three straight-chain alkanes.

$CH_3CH_2CH_2CH_3$	$CH_3CH_2CH_2CH_2CH_3$	$CH_3CH_2CH_2CH_2CH_2CH_3$
butane	pentane	hexane
bp = −0.5 °C	bp = 36 °C	bp = 69 °C

Increasing surface area
Increasing boiling point

Because nonpolar alkanes are water insoluble and less dense than water, crude petroleum spilled into the sea from a ruptured oil tanker creates an insoluble oil slick on the surface. The insoluble hydrocarbon oil poses a special threat to birds whose feathers are coated with natural nonpolar oils for insulation. Because these oils dissolve in the crude petroleum, birds lose their layer of natural protection and many die.

ENVIRONMENTAL NOTE



Crude oil that leaks into the sea forms an insoluble layer on the surface.

PROBLEM 12.19 Rank the following products of petroleum refining in order of increasing boiling point: diesel fuel, kerosene, and gasoline.

PROBLEM 12.20

Answer the following questions about pentane (C_5H_{12}), heptane (C_7H_{16}), and decane ($C_{10}H_{22}$).

a. Which compound has the highest boiling point?
b. Which compound has the lowest boiling point?
c. Which compound has the highest melting point?
d. Which compound has the lowest melting point?

The insolubility of nonpolar oil and very polar water leads to the expression, "Oil and water don't mix."

12.8 FOCUS ON THE ENVIRONMENT COMBUSTION

Alkanes are the only family of organic molecules that has no functional group, so **alkanes undergo few reactions.** In this chapter, we consider only one reaction of alkanes—**combustion.** Combustion is an example of an **oxidation–reduction** reaction, a class of reactions first discussed in Section 5.8.

To determine if an organic compound undergoes oxidation or reduction, we concentrate on the carbon atoms of the starting material and product, and **compare the relative number of C—H and C—O bonds.**

- ***Oxidation* results in an *increase* in the number of C—O bonds or a *decrease* in the number of C—H bonds.**
- ***Reduction* results in a *decrease* in the number of C—O bonds or an *increase* in the number of C—H bonds.**

Alkanes undergo **combustion**—that is, **they burn in the presence of oxygen to form carbon dioxide (CO_2) and water.** This is a practical example of oxidation. Every C—H and C—C bond in the starting material is converted to a C—O bond in the product. Equations are written with two different alkanes.

Review Section 5.2 on how to balance a chemical equation.

$$\underset{\text{methane (natural gas)}}{CH_4} + 2\ O_2 \xrightarrow{\text{flame}} CO_2 + 2\ H_2O + \text{energy}$$

$$\underset{\text{isooctane (high-octane component of gasoline)}}{2\ (CH_3)_3CCH_2CH(CH_3)_2} + 25\ O_2 \xrightarrow{\text{flame}} 16\ CO_2 + 18\ H_2O + \text{energy}$$

Note that the products, $\mathbf{CO_2 + H_2O}$, are the same regardless of the identity of the starting material. Combustion of alkanes in the form of natural gas, gasoline, or heating oil releases energy for heating homes, powering vehicles, and cooking food.

A spark or a flame is needed to initiate combustion. Gasoline, which is composed largely of alkanes, can be safely handled and stored in the air, but the presence of a spark or open flame causes immediate and violent combustion.

ENVIRONMENTAL NOTE



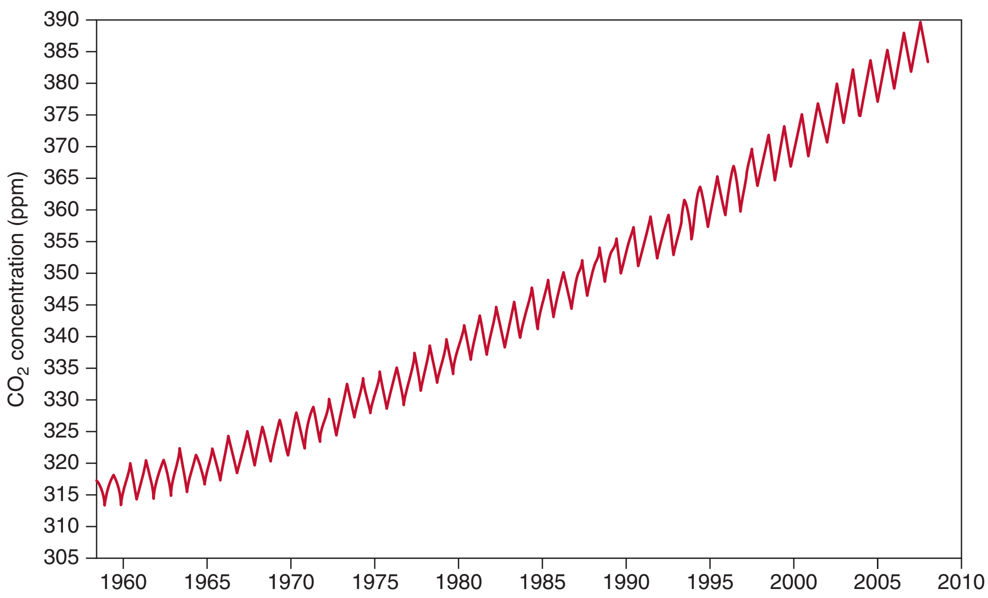
Driving an automobile 10,000 miles at 25 miles per gallon releases 10,000 lb of CO_2 into the atmosphere.

The combustion of alkanes and other hydrocarbons obtained from fossil fuels adds a tremendous amount of CO_2 to the atmosphere each year. Quantitatively, data show over a 20% increase in the atmospheric concentration of CO_2 in the last 50 years (from 315 parts per million in 1958 to 386 parts per million in 2007; Figure 12.2). Although the composition of the atmosphere has changed over the lifetime of the earth, this is likely the first time that the actions of mankind have altered that composition significantly and so quickly.

An increased CO_2 concentration in the atmosphere may have long-range and far-reaching effects. CO_2 is a **greenhouse gas** because it absorbs thermal energy that normally radiates from the

The 2007 Nobel Peace Prize was awarded to former Vice President Al Gore and the Intergovernmental Panel on Climate Change for their roles in focusing attention on the potentially disastrous effects of rapid climate change caused by human activity.

FIGURE 12.2 The Changing Concentration of CO_2 in the Atmosphere



The graph clearly shows the increasing level of CO_2 in the atmosphere (1958–2007). Two data points are recorded each year. The sawtooth nature of the graph is due to seasonal variation of CO_2 level with the seasonal variation in photosynthesis. (Data recorded at Mauna Loa, Hawaii.)

earth's surface, and redirects it back to the surface. Higher levels of CO_2 may therefore contribute to an increase in the average temperature of the earth's atmosphere. This **global warming,** as it has been termed, has many consequences—the melting of polar ice caps, the rise in sea level, and drastic global climate changes to name a few.

PROBLEM 12.21

Write a balanced equation for each combustion reaction.

a. $CH_3CH_2CH_3 + O_2 \xrightarrow{\text{flame}}$ (propane)

b. $CH_3CH_2CH_2CH_3 + O_2 \xrightarrow{\text{flame}}$ (butane)

When there is not enough oxygen available to completely burn a hydrocarbon, **incomplete combustion** may occur and **carbon monoxide** (CO) is formed instead of carbon dioxide (CO_2).

Incomplete combustion

$$2\ CH_4 + 3\ O_2 \xrightarrow{\text{flame}} 2\ CO + 4\ H_2O + \text{energy}$$

methane; carbon monoxide

HEALTH NOTE

Meters that measure CO levels can be purchased, as described in Section 5.5. When wood is burned in a poorly ventilated fireplace situated in a well-insulated room, the CO concentration can reach an unhealthy level.

Carbon monoxide is a poisonous gas that binds to hemoglobin in the blood, thus reducing the amount of oxygen that can be transported through the bloodstream to cells. CO can be formed whenever hydrocarbons burn. When an automobile engine burns gasoline, unwanted carbon monoxide can be produced. Yearly car inspections measure CO and other pollutant levels and are designed to prevent cars from emitting potentially hazardous substances into ambient air. Carbon monoxide is also formed when cigarettes burn, so heavy smokers have an unhealthy concentration of CO in their bloodstream.

PROBLEM 12.22

Write a balanced equation for the incomplete combustion of ethane (CH_3CH_3) to form carbon monoxide as one product.

CHAPTER HIGHLIGHTS

KEY TERMS

Acyclic alkane (12.1)
Alkane (12.1)
Alkyl group (12.4)
Branched-chain alkane (12.2)
Combustion (12.8)
Constitutional isomer (12.2)
Cycloalkane (12.1)
Greenhouse gas (12.8)
Incomplete combustion (12.8)
Isomer (12.2)
IUPAC nomenclature (12.3)
Oxidation (12.8)
Parent name (12.4)
Petroleum (12.6)
Pheromone (12.1)
Primary carbon, 1° C (12.2)
Quaternary carbon, 4° C (12.2)
Reduction (12.8)
Refining (12.6)
Saturated hydrocarbon (12.1)
Secondary carbon, 2° C (12.2)
Straight-chain alkane (12.2)
Tertiary carbon, 3° C (12.2)

KEY CONCEPTS

1 What are the characteristics of an alkane? (12.1, 12.2)

- Alkanes are hydrocarbons having only nonpolar C—C and C—H single bonds.
- There are two types of alkanes: Acyclic alkanes (C_nH_{2n+2}) have no rings. Cycloalkanes (C_nH_{2n}) have one or more rings.
- A carbon is classified as 1°, 2°, 3°, or 4° by the number of carbons bonded to it. A 1° C is bonded to one carbon; a 2° C is bonded to two carbons, and so forth.

2 What are constitutional isomers? (12.2)

- Isomers are different compounds with the same molecular formula.
- Constitutional isomers differ in the way the atoms are connected to each other. $CH_3CH_2CH_2CH_3$ and $HC(CH_3)_3$ are constitutional isomers because they have molecular formula C_4H_{10} but one compound has a chain of four carbons in a row and the other does not.

3 How are alkanes named? (12.4, 12.5)

- Alkanes are named using the IUPAC system of nomenclature. A name has three parts: the parent indicates the number of carbons in the longest chain or the ring; the suffix indicates the functional group (*-ane* = alkane); the prefix tells the number and location of substituents coming off the chain or ring.
- Alkyl groups are formed by removing one hydrogen from an alkane. Alkyl groups are named by changing the *-ane* ending of the parent alkane to the suffix *-yl*.

4 Characterize the physical properties of alkanes. (12.7)

- Alkanes are nonpolar, so they have weak intermolecular forces, low melting points, and low boiling points.
- The melting points and boiling points of alkanes increase as the number of carbons increases due to increased surface area.
- Alkanes are insoluble in water.

5 What are the products of the combustion and incomplete combustion of an alkane? (12.8)

- Alkanes burn in the presence of air. Combustion forms CO_2 and H_2O as products. Incomplete combustion forms CO and H_2O.
- Alkane combustion has increased the level of CO_2, a greenhouse gas, in the atmosphere.
- Incomplete combustion forms carbon monoxide, a toxin and air pollutant.

PROBLEMS

Selected in-chapter and end-of-chapter problems have brief answers provided in Appendix B.

Alkanes and Isomers

12.23 The waxy coating that covers tobacco leaves contains a straight-chain alkane having 31 carbons. How many hydrogens does this alkane contain?

12.24 The largest known cycloalkane with a single ring has 288 carbons. What is its molecular formula?

12.25 The sex attractant of the female tiger moth is an alkane of molecular formula $C_{18}H_{38}$. Is this molecule an acyclic alkane or a cycloalkane?

12.26 In addition to other compounds, beeswax contains an acyclic alkane that has 64 hydrogens. How many carbon atoms does this alkane contain?

12.27 Paraffin wax is a mixture of straight- and branched-chain alkanes having 26–30 carbons. How many hydrogens does each of these alkanes contain?

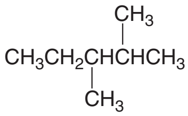
12.28 An alkane has 20 hydrogen atoms. How many carbon atoms would it contain if it were (a) a straight-chain alkane; (b) a branched-chain alkane; (c) a cycloalkane?

12.29 Explain why a cycloalkane has two fewer hydrogen atoms than an acyclic alkane with the same number of carbon atoms.

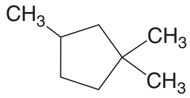
12.30 What is the difference between a branched-chain alkane and a cycloalkane?

12.31 Classify each carbon as 1°, 2°, 3°, or 4°.

a. $CH_3(CH_2)_3CH_3$

b. 

c. $(CH_3)_3CC(CH_3)_3$

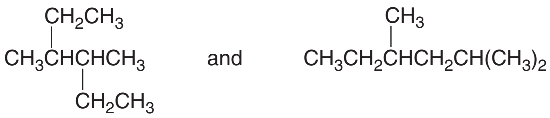
d. 

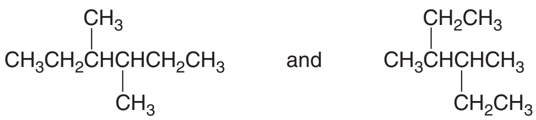
12.32 Give the structure of an alkane that fits each description.
a. an alkane that contains only 1° and 4° carbons
b. a cycloalkane that contains only 2° carbons
c. an alkane of molecular formula C_6H_{14} that contains a 4° carbon
d. a cycloalkane that contains 2° and 3° carbons

12.33 Draw the structure of an alkane with molecular formula C_7H_{16} that (a) contains one 4° carbon; (b) contains only 1° and 2° carbons.

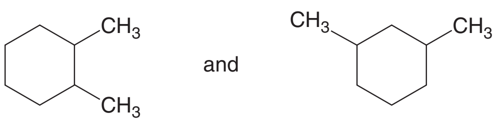
12.34 Is it possible to have an alkane that contains only 1° carbons? Explain why or why not with an example.

12.35 Label each pair of compounds as constitutional isomers or identical molecules.

a. 

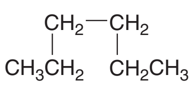
b. 

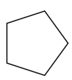
c. 

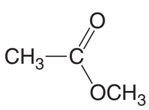
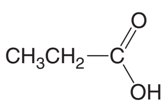
d. 

12.36 Label each pair of compounds as constitutional isomers, identical molecules, or not isomers of each other.

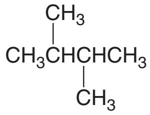
a. $CH_3CH_2CH_2CH_3$ and $CH_3CH_2CH_2CH_2CH_3$

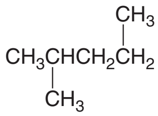
b.  and $CH_3(CH_2)_4CH_3$

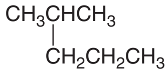
c. $CH_3CH_2CH_2CH_2CH_3$ and 

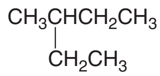
d.  and 

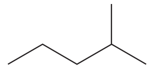
12.37 How is each of the following compounds related to $(CH_3)_2CHCH_2CH_2CH_3$? Choose from constitutional isomers or identical molecules.

a. 

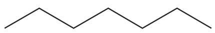
b. 

c. 

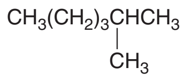
d. 

e. 

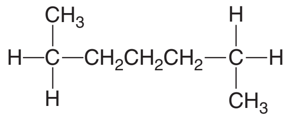
12.38 Consider compounds **A–E** and label each pair of compounds as identical molecules, constitutional isomers, or not isomers of each other: (a) **A** and **B;** (b) **A** and **C;** (c) **B** and **D;** (d) **D** and **E;** (e) **B** and **E.**



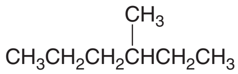
A



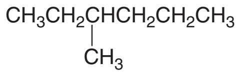
B



C



D



E

12.39 Draw structures that fit the following descriptions:
a. two cycloalkanes that are constitutional isomers with molecular formula C_7H_{14}
b. an ether and an alcohol that are constitutional isomers with molecular formula $C_5H_{12}O$
c. two constitutional isomers of molecular formula C_3H_7Cl

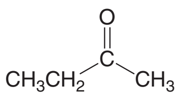
12.40 Draw the five constitutional isomers having molecular formula C_6H_{14}.

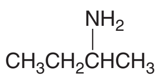
12.41 Draw all constitutional isomers having molecular formula C_8H_{18} that contain seven carbons in the longest chain and a single CH_3 group bonded to the chain.

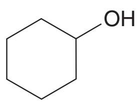
12.42 Draw the five constitutional isomers that have molecular formula C_5H_{10} and contain one ring.

12.43 Draw three constitutional isomers with molecular formula C_3H_6O. Draw the structure of one alcohol, one ketone, and one cyclic ether.

12.44 Draw one constitutional isomer of each compound.

a. 

b. 

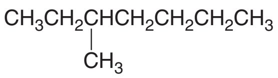
c. 

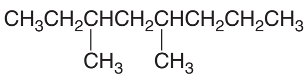
Alkane Nomenclature

12.45 Give the IUPAC name for each of the five constitutional isomers of molecular formula C_6H_{14} in Problem 12.40.

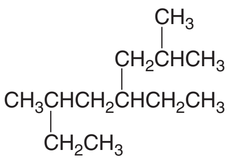
12.46 Give the IUPAC name for each of the five cyclic isomers of molecular formula C_5H_{10} in Problem 12.42.

12.47 Give the IUPAC name for each compound.

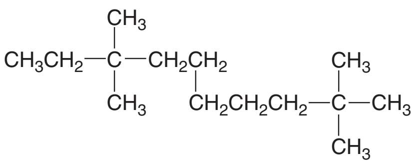
a. 

b. 

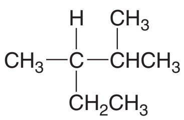
c. $CH_3CH_2CH_2C(CH_2CH_3)_3$

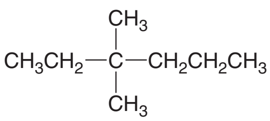
d. 

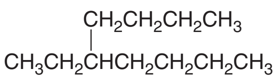
e. $(CH_3CH_2)_2CHCH_2CH_2CH_2CH(CH_3)_2$

f. 

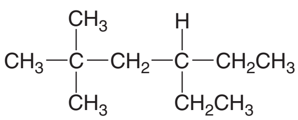
12.48 Give the IUPAC name for each compound.

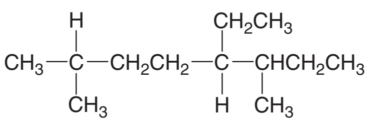
a. 

b. 

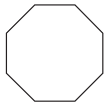
c. 

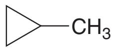
d. $(CH_3CH_2)_2CHCH(CH_2CH_3)_2$

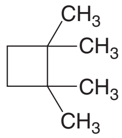
e. 

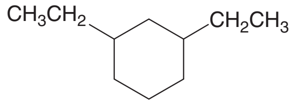
f. 

12.49 Give the IUPAC name for each cycloalkane.

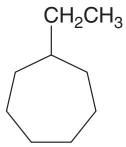
a. 

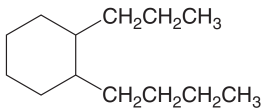
b. 

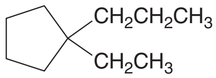
c. 

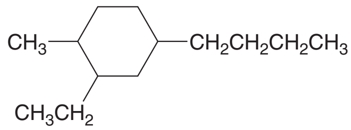
d. 

12.50 Give the IUPAC name for each cycloalkane.

a. 

b. 

c. 

d. 

12.51 Give the structure corresponding to each IUPAC name.
a. 3-ethylhexane
b. 3-ethyl-3-methyloctane
c. 2,3,4,5-tetramethyldecane
d. cyclononane
e. 1,1,3-trimethylcyclohexane
f. 1-ethyl-2,3-dimethylcyclopentane

12.52 Give the structure corresponding to each IUPAC name.
a. 3-ethyl-3-methylhexane
b. 2,2,3,4-tetramethylhexane
c. 4-ethyl-2,2-dimethyloctane
d. 1,3,5-triethylcycloheptane
e. 3-ethyl-3,4-dimethylnonane
f. 2-ethyl-1-methyl-3-propylcyclopentane

12.53 Each of the following IUPAC names is incorrect. Explain why it is incorrect and give the correct IUPAC name.
a. 3-methylbutane
b. 1-methylcyclopentane
c. 1,3-dimethylbutane
d. 5-ethyl-2-methylhexane
e. 1,5-dimethylcyclohexane
f. 1-propyl-2-ethylcyclopentane

12.54 Each of the following IUPAC names is incorrect. Explain why it is incorrect and give the correct IUPAC name.
a. 4-methylpentane
b. 2,3,3-trimethylbutane
c. 1,3-dimethylpentane
d. 3-methyl-5-ethylhexane
e. 2-ethyl-2-methylcycloheptane
f. 1,6-diethylcyclohexane

12.55 Draw three constitutional isomers having molecular formula C_7H_{14} that contain a five-membered ring and two CH_3 groups bonded to the ring. Give the IUPAC name for each isomer.

12.56 Draw four constitutional isomers having molecular formula C_6H_{12} that contain a four-membered ring. Give the IUPAC name for each isomer.

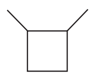
Drawing Acyclic Alkanes and Cycloalkanes

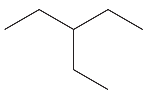
12.57 Draw a skeletal structure for each compound.
a. octane
b. 1,2-dimethylcyclopentane
c. $CH_3CHCH_2CH_2CH_2CH_2CH_3$ (with CH_3 on C2)

12.58 Convert each compound to a skeletal structure.
a. $CH_3(CH_2)_7CH_3$
b. 1,1-diethylcyclohexane
c. $(CH_3CH_2)_2CHCH_2CH_2CH_3$

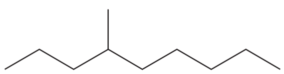
12.59 Convert each skeletal structure to a complete structure with all atoms drawn in.

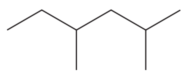
a. 

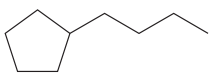
c. 

b. 

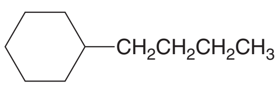
12.60 Convert each skeletal structure to a complete structure with all atoms drawn in.

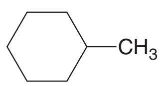
a. 

c. 

b. 

Physical Properties

12.61 Which compound in each pair has the higher melting point?
a. $CH_3CH_2CH_3$ or $CH_3CH_2CH_2CH_3$
b. 

or 

12.62 Which compound in each pair has the higher boiling point?
a. cyclobutane or cyclopentane
b. cyclopentane or ethylcyclopentane

12.63 Branching in an alkane chain decreases surface area. As a result, a branched-chain alkane tends to have a lower boiling point than a straight-chain alkane with the same number of carbons. Keeping this in mind, rank the alkane isomers in each group in order of increasing boiling point.
a. $CH_3CH_2CH_2CH_2CH_3$, $(CH_3)_2CHCH_2CH_3$, $(CH_3)_4C$
b. $(CH_3)_2CHCH(CH_3)_2$, $CH_3(CH_2)_4CH_3$, $CH_3CH_2CH_2CH(CH_3)_2$

12.64 Explain why the boiling points of heptane $[CH_3(CH_2)_5CH_3]$ and H_2O are similar even though heptane has a much higher molecular weight and greater surface area.

12.65 Explain why hexane is more soluble in dichloromethane (CH_2Cl_2) than in water.

12.66 Mineral oil and Vaseline are both mixtures of alkanes, but mineral oil is a liquid at room temperature and Vaseline is a solid. Which product is composed of alkanes that contain a larger number of carbon atoms? Explain your choice.

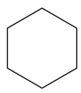
Reactions

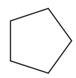
12.67 What products are formed from the combustion of an alkane?

12.68 What products are formed from the incomplete combustion of an alkane?

12.69 Write a balanced equation for the combustion of each alkane: (a) CH_3CH_3; (b) $(CH_3)_2CHCH_2CH_3$.

12.70 Write a balanced equation for the combustion of each cycloalkane.

a. 

b. 

12.71 Write a balanced equation for the incomplete combustion of each alkane: (a) $CH_3CH_2CH_3$; (b) $CH_3CH_2CH_2CH_3$.

12.72 Benzene (C_6H_6) is a fuel additive sometimes used to make gasoline burn more efficiently. Write a balanced equation for the incomplete combustion of benzene.

12.73 In the body, glucose, a simple carbohydrate with molecular formula $C_6H_{12}O_6$, is oxidized to CO_2 and H_2O with the release of a great deal of energy. Thus, the metabolism of glucose provides energy for our bodies, in much the same way as the oxidation of an alkane provides energy to power an automobile. Write a balanced equation for the oxidation of glucose to form CO_2 and H_2O.

12.74 Gasohol is a mixture of 90% gasoline and 10% ethanol, CH_3CH_2OH. Ethanol is considered an environmentally friendly fuel additive because it can be made from a renewable source—sugarcane. Ethanol burns in air to form CO_2 and H_2O, and, like the combustion of alkanes, this reaction also releases a great deal of energy. Write a balanced equation for the combustion of ethanol.

Applications

12.75 The gasoline industry seasonally changes the composition of gasoline in locations where it gets very hot in the summer and very cold in the winter. Gasoline is refined to contain a larger fraction of higher molecular weight alkanes in warmer weather. In colder weather, it is refined to contain a larger fraction of lower molecular weight alkanes. What is the purpose of producing different types of gasoline for different temperatures?

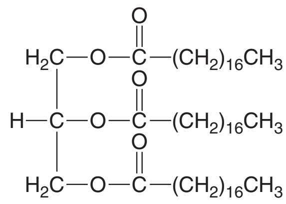
12.76 Polyethylene (Section 11.5) is a high molecular weight alkane that contains hundreds or even thousands of carbon atoms, bonded together in long carbon chains. When a new home is built, the concrete foundation is often wrapped with polyethylene (sold under the trade name of Tyvek). What purpose does the polyethylene serve?

12.77 Mineral oil, a mixture of high molecular weight alkanes, is sometimes used as a laxative. Individuals who use mineral oil for this purpose are advised to avoid taking it at the same time they consume foods rich in fat-soluble vitamins such as vitamin A. Why is this advice given?

12.78 Explain why having a fire in a fireplace in a poorly ventilated room poses a health hazard.

12.79 You went running on a newly paved asphalt road, which soiled your sneakers. What solvent might be best for removing asphalt, a mixture of high molecular weight hydrocarbons, from your sneakers: (a) water; (b) nail polish remover, which is mainly acetone [$(CH_3)_2C{=}O$]; (c) paint thinner, which is largely liquid alkanes? Explain your choice.

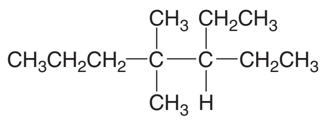
12.80 A major component of animal fat is tristearin. (a) Identify the three functional groups in tristearin. (b) Label all the polar bonds. (c) Explain why tristearin will dissolve in an organic solvent like hexane, but is insoluble in water.



tristearin

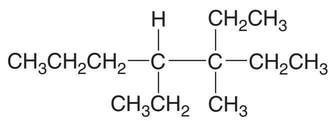
General Questions

12.81 Answer the following questions about the alkane drawn below.



a. Give the IUPAC name.
b. Draw one constitutional isomer.
c. Predict the solubility in water.
d. Predict the solubility in an organic solvent.
e. Write a balanced equation for complete combustion.
f. Draw a skeletal structure.

12.82 Answer the following questions about the alkane drawn below.



a. Give the IUPAC name.
b. Draw one constitutional isomer.
c. Predict the solubility in water.
d. Predict the solubility in an organic solvent.
e. Write a balanced equation for complete combustion.
f. Draw a skeletal structure.

CHALLENGE QUESTIONS

12.83 What is the molecular formula for a compound with 10 carbons and two rings?

12.84 Draw the structure of the 12 constitutional isomers that have the molecular formula C_6H_{12} and contain one ring.

12.85 Cyclopentane has a higher boiling point than pentane even though both compounds have the same number of carbons (49 °C vs. 36 °C). Can you suggest a reason for this phenomenon?

12.86 Draw the structure of the seven constitutional isomers having molecular formula $C_4H_{10}O$. Each compound is either an ether or an alcohol.

13

CHAPTER OUTLINE

CHAPTER GOALS

In this chapter you will learn how to:

1. Identify the three major types of unsaturated hydrocarbons—alkenes, alkynes, and aromatic compounds
2. Name alkenes, alkynes, and substituted benzenes
3. Recognize the difference between constitutional isomers and stereoisomers, as well as identify cis and trans isomers
4. Identify saturated and unsaturated fatty acids and predict their relative melting points
5. Draw the products of addition reactions of alkenes
6. Draw the products of reactions that follow Markovnikov's rule
7. Explain what products are formed when a vegetable oil is partially hydrogenated
8. Draw the structure of polymers formed from alkene monomers
9. Draw the products of substitution reactions of benzene



Vegetable oils obtained from olives, peanuts, and corn are formed from unsaturated organic molecules such as oleic acid and linoleic acid.

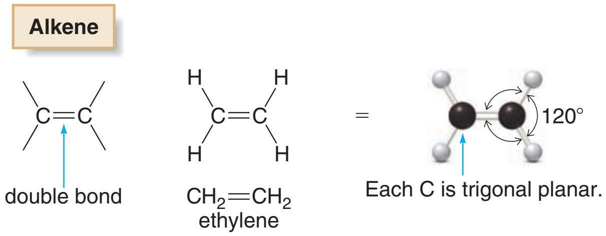
UNSATURATED HYDROCARBONS

IN Chapter 13 we continue our study of hydrocarbons by examining three families of compounds that contain carbon–carbon multiple bonds. **Alkenes** contain a double bond and **alkynes** contain a triple bond. **Aromatic hydrocarbons** contain a benzene ring, a six-membered ring with three double bonds. These compounds differ from the alkanes of Chapter 12 because they each have a functional group, making them much more reactive. Thousands of biologically active molecules contain these functional groups, and many useful synthetic products result from their reactions.

13.1 ALKENES AND ALKYNES

Alkenes and alkynes are two families of organic molecules that contain multiple bonds.

- **Alkenes are compounds that contain a carbon–carbon double bond.**



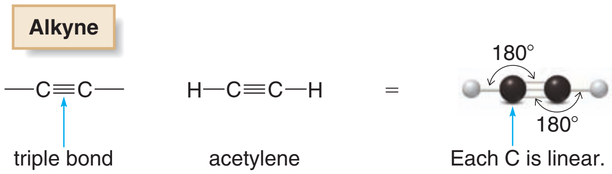


A ripe banana speeds up the ripening of green tomatoes because the banana gives off ethylene, a plant growth hormone.

The general molecular formula of an alkene is $\mathbf{C_nH_{2n}}$, so an alkene has **two** fewer hydrogens than an acyclic alkane, which has a general molecular formula of C_nH_{2n+2}. Ethylene (C_2H_4) is the simplest alkene. Since each carbon of ethylene is surrounded by three atoms, each carbon is **trigonal planar.** All six atoms of ethylene lie in the same plane, and all bond angles are **120°.**

Ethylene is a hormone that regulates plant growth and fruit ripening. This allows individuals to enjoy bananas, strawberries, and tomatoes that were grown in faraway countries. Fruit can be picked green, and then sprayed with ethylene when ripening is desired upon arrival at its destination.

- **Alkynes are compounds that contain a carbon–carbon triple bond.**



The general molecular formula for an alkyne is $\mathbf{C_nH_{2n-2}}$, so an alkyne has **four** fewer hydrogens than an acyclic alkane. Acetylene (C_2H_2) is the simplest alkyne. Each carbon of acetylene is surrounded by two atoms, making each carbon **linear** with bond angles of **180°.**

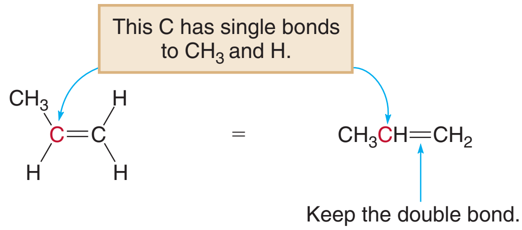
Because alkenes and alkynes are composed of nonpolar carbon–carbon and carbon–hydrogen bonds, their physical properties are similar to other hydrocarbons. Like alkanes:

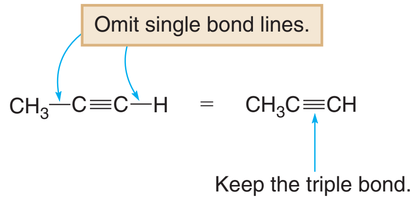
- **Alkenes and alkynes have low melting points and boiling points and are insoluble in water.**

Recall from Chapter 12 that acyclic alkanes are called saturated hydrocarbons, because they contain the maximum number of hydrogen atoms per carbon. In contrast, **alkenes and alkynes are called *unsaturated* hydrocarbons.**

- **Unsaturated hydrocarbons are compounds that contain fewer than the maximum number of hydrogen atoms per carbon.**

The multiple bond of an alkene or alkyne is always drawn in a condensed structure. To translate a condensed structure to a complete structure with all bond lines drawn in, make sure that each carbon of a double bond has three atoms around it, and each carbon of a triple bond has two atoms around it, as shown in Sample Problem 13.1. Keep in mind that in every structure, each carbon always has four bonds.





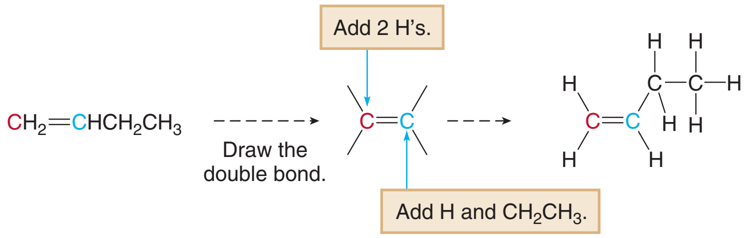
SAMPLE PROBLEM 13.1

Draw a complete structure for each alkene or alkyne.

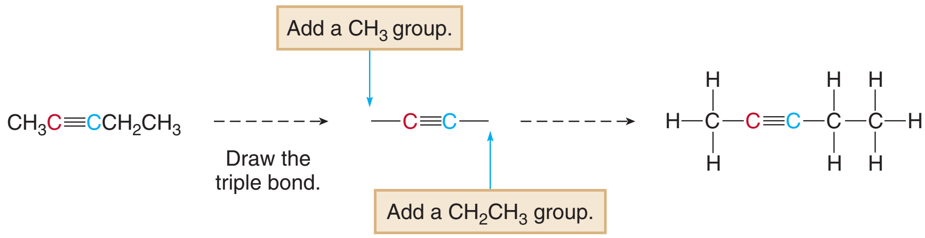
a. $CH_2{=}CHCH_2CH_3$ b. $CH_3C{\equiv}CCH_2CH_3$

ANALYSIS First, draw the multiple bond in each structure. Draw an alkene so that each C of the double bond has three atoms around it. Draw an alkyne so that each C of the triple bond has two atoms around it. All other C's have four single bonds.

SOLUTION a. The C labeled in red, has single bonds to 2 H's. The C labeled in blue has single bonds to 1 H and a CH_2CH_3 group.



b. The C labeled in red has a single bond to a CH_3 group. The C labeled in blue has a single bond to a CH_2CH_3 group.



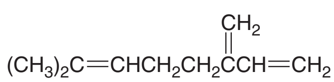
PROBLEM 13.1

Convert each condensed structure to a complete structure with all atoms and bond lines drawn in.

a. $CH_2{=}CHCH_2OH$ b. $(CH_3)_2C{=}CH(CH_2)_2CH_3$ c. $(CH_3)_2CHC{\equiv}CCH_2C(CH_3)_3$

PROBLEM 13.2

Myrcene is an alkene obtained from the bayberry plant. Draw a complete structure for myrcene with all atoms and bond lines.



myrcene

PROBLEM 13.3

Determine whether each molecular formula corresponds to a saturated hydrocarbon, an alkene, or an alkyne.

a. C_3H_6 b. C_5H_{12} c. C_8H_{14} d. C_6H_{12}

PROBLEM 13.4

Give the molecular formula for each of the following compounds.

a. an alkene that has four carbons
b. a saturated hydrocarbon that has six carbons
c. an alkyne that has seven carbons
d. an alkene that has five carbons

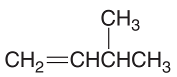
13.2 NOMENCLATURE OF ALKENES AND ALKYNES

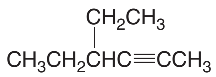
Whenever we encounter a new functional group, we must learn how to use the IUPAC system to name it. There are two new facts to learn: how to name the suffix that identifies the functional group, and how to number the carbon skeleton. In the IUPAC system:

- **An alkene is identified by the suffix *-ene.***
- **An alkyne is identified by the suffix *-yne.***

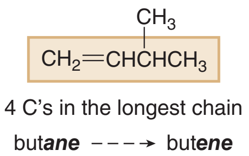
HOW TO Name an Alkene or an Alkyne

EXAMPLE **Give the IUPAC name of each alkene and alkyne.**

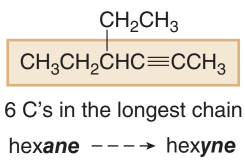
a. 

b. 

Step [1] **Find the longest chain that contains *both* carbon atoms of the double or triple bond.**

a. 

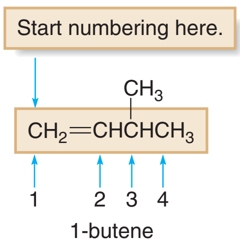
- Since the compound is an alkene, change the ***-ane*** ending of the parent alkane to ***-ene.***

b. 

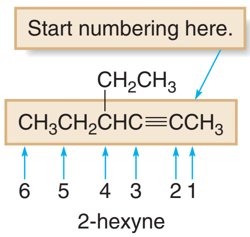
- Since the compound is an alkyne, change the ***-ane*** ending of the parent alkane to ***-yne.***

Step [2] **Number the carbon chain from the end that gives the multiple bond the lower number.**

For each compound, number the chain and name the compound using the *first* number assigned to the multiple bond.

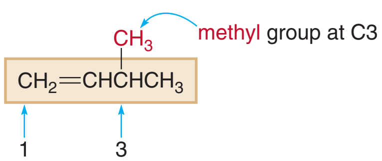
a. 

- Numbering the chain from left to right puts the double bond at C1 (not C3). The alkene is named using the *first* number assigned to the double bond, making it 1-butene.

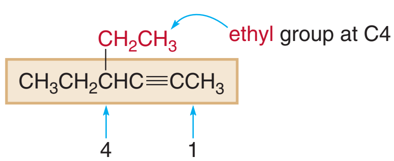
b. 

- Numbering the chain from right to left puts the triple bond at C2 (not C4). The alkyne is named using the *first* number assigned to the triple bond, making it 2-hexyne.

Step [3] **Number and name the substituents, and write the name.**

a. 

Answer: 3-methyl-1-butene

b. 

Answer: 4-ethyl-2-hexyne

Compounds with two double bonds are called **dienes.** They are named by changing the *-ane* ending of the parent alkane to the suffix *-adiene.* Each double bond gets its own number.

$CH_2{=}CHCH{=}CH_2$

Numbering: 1 2 3 4

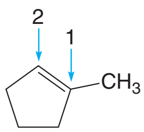
Name: **1,3-butadiene**

$CH_3C(CH_3){=}CHCH_2CH{=}CH_2$

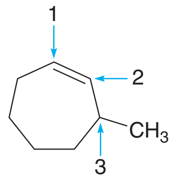
Numbering: 6 5 4 3 2 1

Name: **5-methyl-1,4-hexadiene**

In naming cycloalkenes, the double bond is located between C1 and C2, and the "1" is usually omitted in the name. The ring is numbered to give the first substituent the lower number.

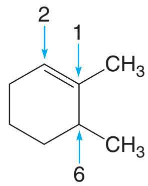


1-methylcyclopentene



3-methylcycloheptene

[Number clockwise beginning at the C=C and place the CH_3 at C3.]



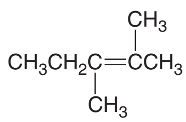
1,6-dimethylcyclohexene

[Number counterclockwise beginning at the C=C and place the first CH_3 at C1.]

A few simple alkenes and alkynes have names that do not follow the IUPAC system. The simplest alkene, $CH_2{=}CH_2$, is called *ethene* in the IUPAC system, but it is commonly called **ethylene.** The simplest alkyne, HC≡CH, is called *ethyne* in the IUPAC system, but it is commonly named **acetylene.** We will use these common names since they are more widely used than their systematic IUPAC names.

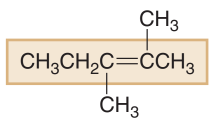
SAMPLE PROBLEM 13.2

Give the IUPAC name for the following compound.



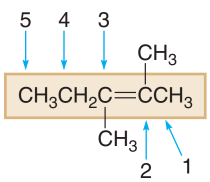
ANALYSIS AND SOLUTION

[1] **Find the longest chain containing both carbon atoms of the multiple bond.**



5 C's in the longest chain ----→ **pentene**

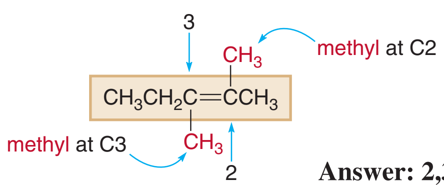
[2] **Number the chain to give the double bond the lower number.**



- Numbering from right to left is preferred since the double bond begins at C2 (not C3). The molecule is named as a **2-pentene.**

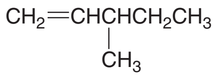
[3] **Name and number the substituents and write the complete name.**

- The alkene has two methyl groups located at C2 and C3. Use the prefix di- before methyl → 2,3-**di**methyl.



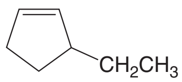
Answer: 2,3-dimethyl-2-pentene

PROBLEM 13.5 Give the IUPAC name for each compound.

a. 

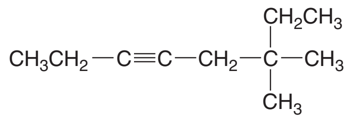
b. $(CH_3CH_2)_2C{=}CHCH_2CH_2CH_3$

c. $CH_3CH_2CH{=}CHCH{=}CHCH_3$

d. 

PROBLEM 13.6 Give the IUPAC name for each compound.

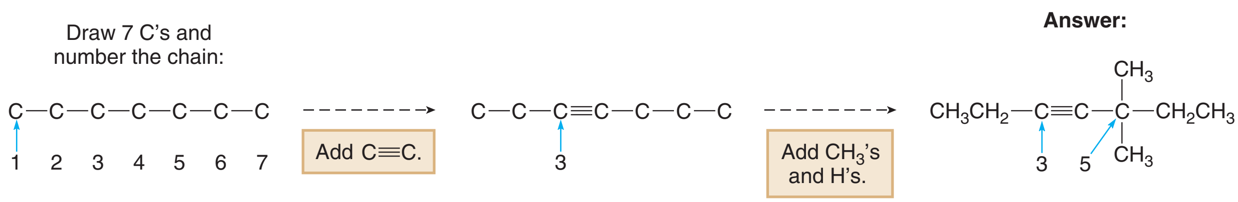
a. $CH_3CH_2CH_2CH_2CH_2C{\equiv}CCH(CH_3)_2$

b. 

SAMPLE PROBLEM 13.3 Draw the structure corresponding to each IUPAC name: (a) 5,5-dimethyl-3-heptyne; (b) 1,3-dimethylcyclohexene.

ANALYSIS First identify the parent name to find the longest carbon chain or ring, and then use the suffix to determine the functional group; the suffix *-ene* = an alkene and *-yne* = an alkyne. Then number the carbon chain or ring and place the functional group at the indicated carbon. Add the substituents and enough hydrogens to give each carbon four bonds.

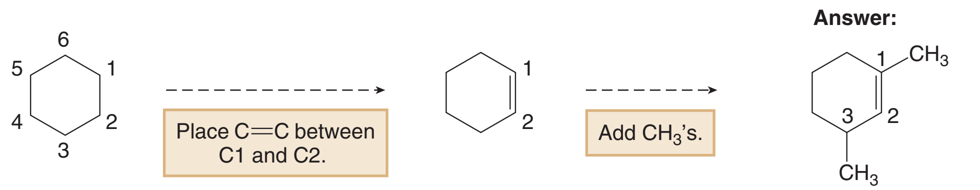
SOLUTION a. 5,5-Dimethyl-3-heptyne has 7 C's as its longest chain (hept-) and a triple bond that begins at C3 (3-heptyne). Two methyl groups are bonded to C5.



5,5-dimethyl-3-heptyne

b. 1,3-Dimethylcyclohexene contains a six-membered ring with a double bond (cyclohexene). Number the ring to put the double bond between C1 and C2, and then add two methyl groups at C1 and C3.

- Draw a 6 C ring.
- Begin numbering at any C.



1,3-dimethylcyclohexene

PROBLEM 13.7 Give the structure corresponding to each of the following names.

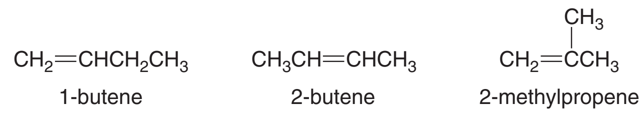
a. 4-methyl-1-hexene
b. 5-ethyl-2-methyl-2-heptene
c. 2,5-dimethyl-3-hexyne
d. 1-propylcyclobutene

PROBLEM 13.8 Give the structure corresponding to each of the following names.

a. 2-methyl-2-octene
b. 5-ethyl-2-methyl-1-nonene
c. 1,3-cyclohexadiene
d. 4-ethyl-1-decyne

13.3 CIS–TRANS ISOMERS

As we learned in Section 12.2 on alkanes, constitutional isomers are possible for alkenes of a given molecular formula. For example, there are three constitutional isomers for an alkene of molecular formula C_4H_8—1-butene, 2-butene, and 2-methylpropene.

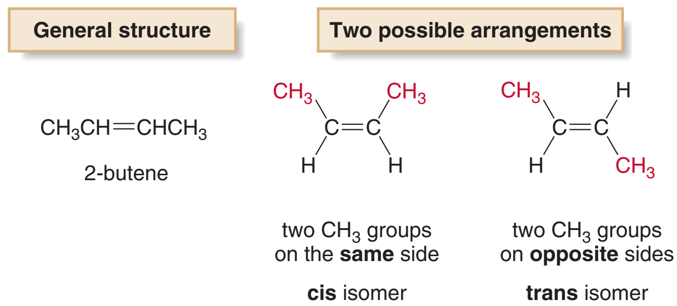


These compounds are constitutional isomers because the atoms are bonded to each other in different ways. 1-Butene and 2-butene both have a four-carbon chain, but the location of the double bond is different, and 2-methylpropene has a longest chain containing only three carbon atoms.

13.3A STEREOISOMERS—A NEW CLASS OF ISOMER

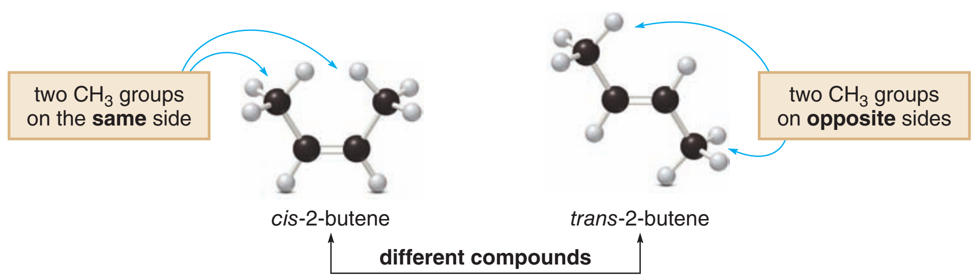
2-Butene illustrates another important aspect about alkenes. In contrast to the free rotation observed around carbon–carbon single bonds (Section 12.2D), there is **restricted rotation** around the carbon atoms of a double bond. As a result, the groups on one side of the double bond *cannot* rotate to the other side.

With 2-butene, there are two ways to arrange the atoms on the double bond. The two CH_3 groups can be on the *same side* of the double bond or they can be on *opposite sides* of the double bond. These molecules are *different* compounds with the same molecular formula; that is, they are **isomers.**

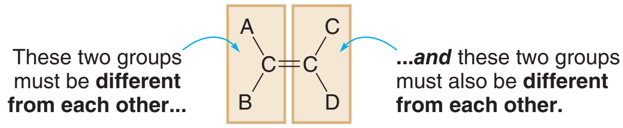


- **When the two CH_3 groups are on the *same side* of the double bond, the compound is called the *cis* isomer.**
- **When the two CH_3 groups are on *opposite sides* of the double bond, the compound is called the *trans* isomer.**

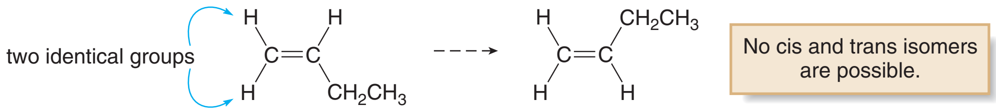
To give these compounds unique IUPAC names, we use the prefixes *cis* and *trans* before the remainder of the name to indicate the relative location of the two alkyl groups on the double bond. Thus, one isomer is called ***cis*-2-butene,** and the other isomer is called ***trans*-2-butene.**



The cis and trans isomers of 2-butene are a specific example of a general class of isomer that occurs at carbon–carbon double bonds. **Whenever the two groups on *each* end of a C=C are *different from each other,* two isomers are possible.**



When the two groups on one end of the double bond are identical, there is still restricted rotation, but no cis and trans isomers are possible. With 1-butene, $CH_2{=}CHCH_2CH_3$, one end of the double bond has two hydrogens, so the ethyl group (CH_2CH_3) is always cis to a hydrogen, no matter how the molecule is drawn.



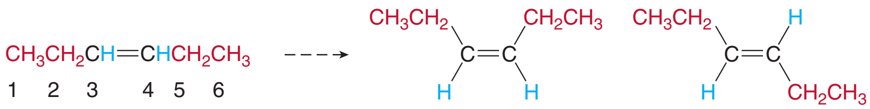
1-butene — identical

SAMPLE PROBLEM 13.4

Draw *cis-* and *trans-*3-hexene.

ANALYSIS First, use the parent name to draw the carbon skeleton, and place the double bond at the correct carbon; 3-hexene indicates a 6 C chain with the double bond beginning at C3. Then use the definitions of cis and trans to draw the isomers.

SOLUTION Each C of the double bond is bonded to a CH_3CH_2 group and a hydrogen. A cis isomer has the CH_3CH_2 groups bonded to the same side of the double bond. A trans isomer has the two CH_3CH_2 groups bonded to the opposite sides of the double bond.



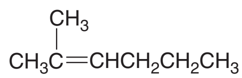
3-hexene — *cis*-3-hexene — *trans*-3-hexene

PROBLEM 13.9

Draw a condensed structure for each compound: (a) *cis*-2-octene; (b) *trans*-3-heptene; (c) *trans*-4-methyl-2-pentene.

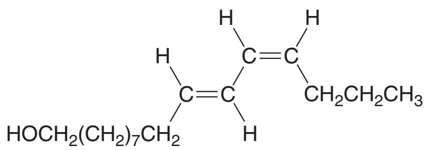
PROBLEM 13.10

For which compounds are cis and trans isomers possible?

a. $CH_3CH_2CH{=}CHCH_3$ b. $CH_2{=}CHCH_2CH_2CH_3$ c. 

PROBLEM 13.11

Bombykol is secreted by the female silkworm moth (*Bombyx mori*) to attract mates. Bombykol contains two double bonds, and each double bond must have a particular three-dimensional arrangement of groups around it to be biologically active. Label the double bonds of bombykol as cis or trans.



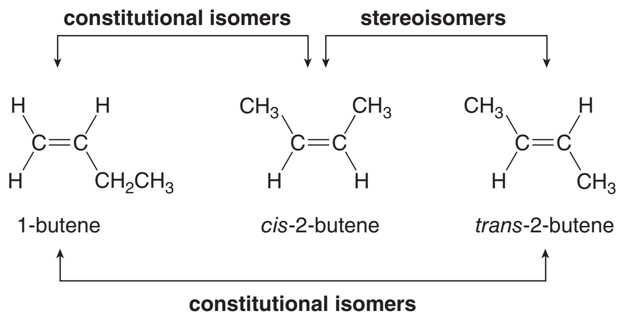
bombykol

ENVIRONMENTAL NOTE



The female silkworm moth, *Bombyx mori,* secretes the sex pheromone bombykol. Pheromones like bombykol have been used to control insect populations. In one method, the pheromone is placed in a trap containing a poison or sticky substance, and the male is lured to the trap by the pheromone. Alternatively, the pheromone can be released into infested areas, confusing males who are then unable to find females.

FIGURE 13.1 Comparing Three Isomers: 1-Butene, *cis*-2-Butene, and *trans*-2-Butene



Cis and trans compounds are isomers, but they are *not* constitutional isomers. Each carbon atom of *cis*- and *trans*-2-butene is bonded to the same atoms. The only difference is the three-dimensional arrangement of the groups around the double bond. Isomers of this sort are called **stereoisomers.**

- ***Stereoisomers* are isomers that differ *only* in the 3-D arrangement of atoms.**

Thus, *cis*-2-butene and *trans*-2-butene are stereoisomers, but each of these compounds is a constitutional isomer of 1-butene, as shown in Figure 13.1.

We have now learned the two major classes of isomers.

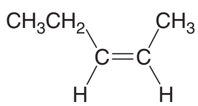
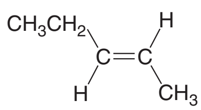
We will learn more about stereoisomers in Chapter 15.

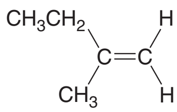
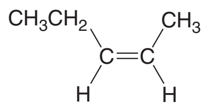
- **Constitutional isomers differ in the way the atoms are bonded to each other.**
- **Stereoisomers differ only in the three-dimensional arrangement of atoms.**

PROBLEM 13.12

Label each pair of alkenes as constitutional isomers or stereoisomers.

a. $CH_3CH{=}CHCH_2CH_3$ and $CH_2{=}CHCH_2CH_2CH_3$

b.  and 

c.  and 

13.3B FOCUS ON HEALTH & MEDICINE SATURATED AND UNSATURATED FATTY ACIDS

Naturally occurring animal fats and vegetable oils are formed from fatty acids. **Fatty acids are carboxylic acids (RCOOH) with long carbon chains of 12–20 carbon atoms.** Because a fatty acid has many nonpolar C—C and C—H bonds and few polar bonds, fatty acids are insoluble in water. There are two types of fatty acids.

- ***Saturated* fatty acids have no double bonds in their long hydrocarbon chains.**
- ***Unsaturated* fatty acids have one or more double bonds in their long hydrocarbon chains.**

TABLE 13.1 Common Saturated and Unsaturated Fatty Acids

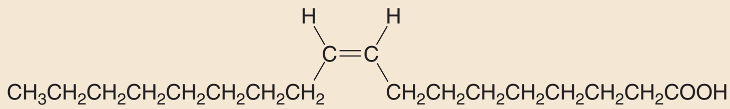
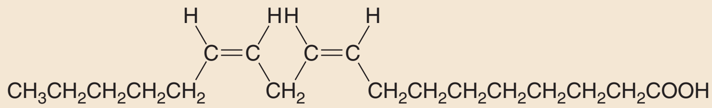
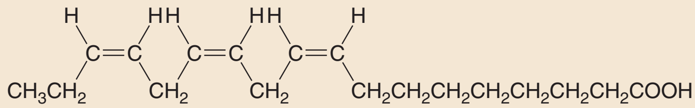
Name	Structure	Mp (°C)
Stearic acid (0 C=C)	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2COOH$	71
Oleic acid (1 C=C)		16
Linoleic acid (2 C=C)		–5
Linolenic acid (3 C=C)		–11

Table 13.1 lists the structure and melting point of four fatty acids containing 18 carbon atoms. Stearic acid is one of the two most common saturated fatty acids, while oleic and linoleic acids are the most common unsaturated ones.

Linoleic and linolenic acids are **essential fatty acids,** meaning they cannot be synthesized in the human body and must therefore be obtained in the diet. A common source of these essential fatty acids is whole milk. Babies fed a diet of nonfat milk in their early months do not thrive because they do not obtain enough of these essential fatty acids.

One structural feature of unsaturated fatty acids is especially noteworthy.

- Generally, double bonds in naturally occurring fatty acids are cis.

The presence of cis double bonds affects the melting point of these fatty acids greatly.

- As the number of double bonds in the fatty acid *increases,* the melting point *decreases.*

The cis double bonds introduce kinks in the long hydrocarbon chain, as shown in Figure 13.2. This makes it difficult for the molecules to pack closely together in a solid. **The larger the number of cis double bonds, the more kinks in the hydrocarbon chain, and the lower the melting point.**

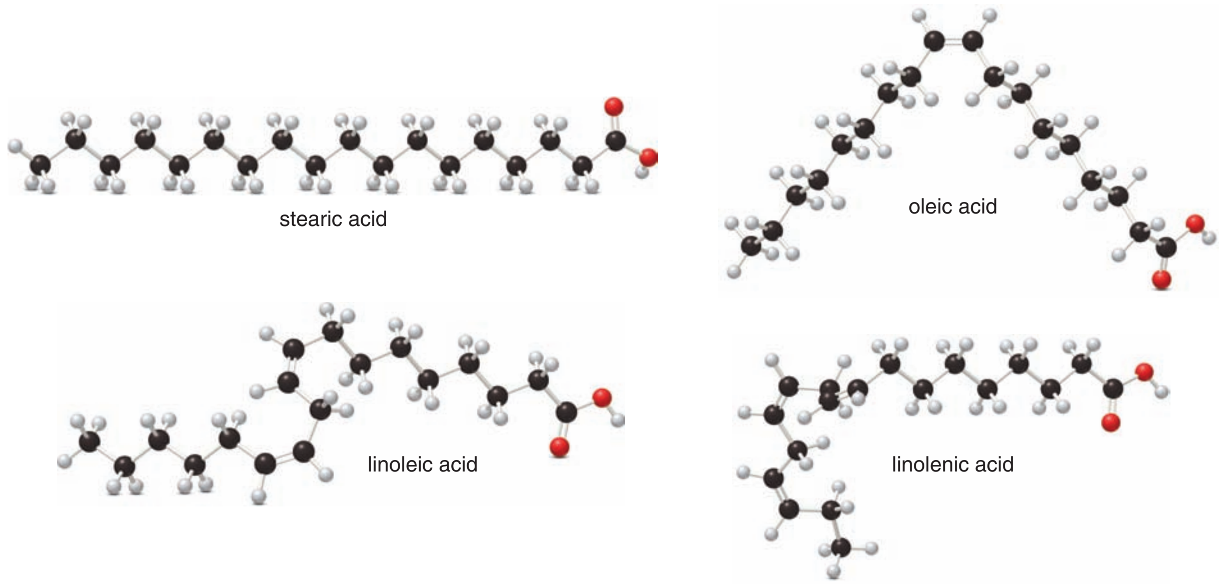
Fats and oils are organic molecules synthesized in plant and animal cells from fatty acids. Fats and oils have different physical properties.

- Fats are solids at room temperature. Fats are generally formed from fatty acids having few double bonds.
- Oils are liquids at room temperature. Oils are generally formed from fatty acids having a larger number of double bonds.

Saturated fats are typically obtained from animal sources, while unsaturated oils are common in vegetable sources. Thus, butter and lard are formed from saturated fatty acids, while olive oil and safflower oil are formed from unsaturated fatty acids. An exception to this generalization is coconut oil, which is composed largely of saturated fatty acids.

Considerable evidence suggests that an elevated cholesterol level is linked to increased risk of heart disease. Saturated fats stimulate cholesterol synthesis in the liver, resulting in an increase in cholesterol concentration in the blood. We will learn more about fats and oils in Section 13.7 and Chapter 19.

FIGURE 13.2 The Three-Dimensional Structure of Four Fatty Acids



PROBLEM 13.13 Draw out a structure of arachidonic acid, indicating the arrangement of groups around the four double bonds.

$$CH_3(CH_2)_4CH{=}CHCH_2CH{=}CHCH_2CH{=}CHCH_2CH{=}CHCH_2(CH_2)_2CO_2H$$

arachidonic acid

PROBLEM 13.14 You have two fatty acids, one with a melting point of 63 °C, and one with a melting point of 1 °C. Which structure corresponds to each melting point?

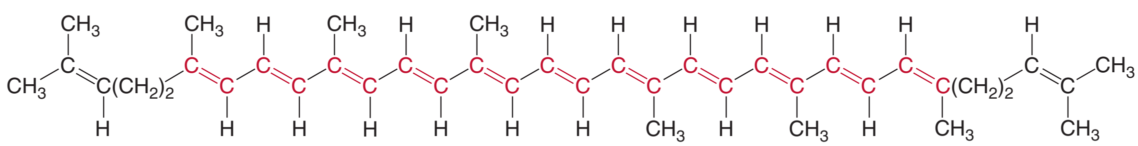
$CH_3(CH_2)_{14}COOH$ (palmitic acid) $\quad$ $CH_3(CH_2)_5CH{=}CH(CH_2)_7COOH$ (palmitoleic acid)

13.4 INTERESTING ALKENES IN FOOD AND MEDICINE

In addition to the plant hormone ethylene, $CH_2{=}CH_2$ (Section 13.1), many useful compounds contain one or more carbon–carbon double bonds.

More examples of antioxidants are given in Section 13.12.

Lycopene, the red pigment in tomatoes and watermelon, contains 13 double bonds. Lycopene is an **antioxidant,** a compound that prevents an unwanted oxidation reaction from occurring. Diets that contain a high intake of antioxidants like lycopene have been shown to decrease the risk of heart disease and certain forms of cancer. Unlike other antioxidants that can be destroyed when fresh fruits or vegetables are processed, even foods such as tomato paste, tomato juice, and ketchup are high in lycopene.



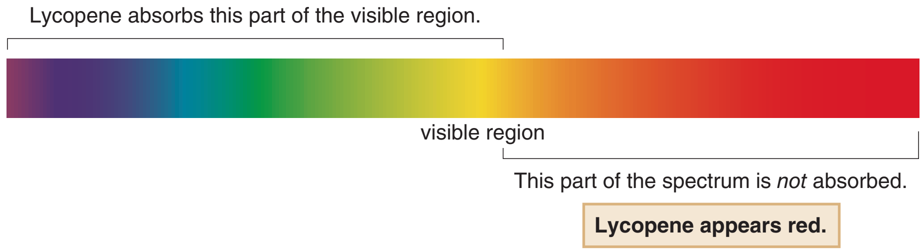
lycopene

HEALTH NOTE

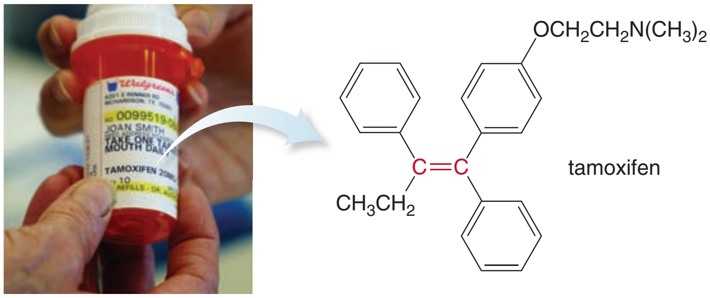


Processed tomato products contain the antioxidant lycopene.

Lycopene's red color is due to the 11 double bonds that are each separated by one single bond (labeled in red). These double bonds absorb some (but not all) wavelengths of visible light. When a compound absorbs visible light, it takes on the color of those wavelengths of light it does *not* absorb. Since lycopene absorbs blue-green light, it appears red because it does not absorb the red light of the visible spectrum.



Tamoxifen is a potent anticancer drug that contains a carbon–carbon double bond in addition to other functional groups. Tamoxifen is used widely in the treatment of certain breast cancers that require the female sex hormone estrogen for growth. Tamoxifen binds to estrogen receptors, and in this way it inhibits the growth of breast cancers that are estrogen dependent. Tamoxifen is sold under the trade name of Novaldex.

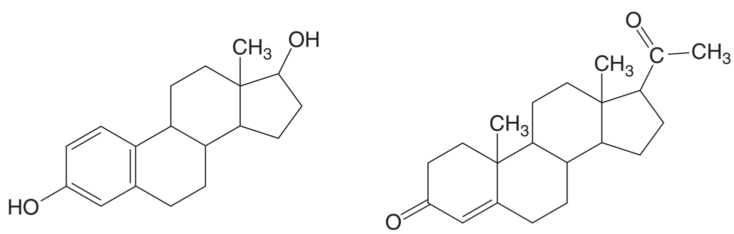


PROBLEM 13.15 Identify all of the functional groups in tamoxifen.

13.5 FOCUS ON HEALTH & MEDICINE ORAL CONTRACEPTIVES

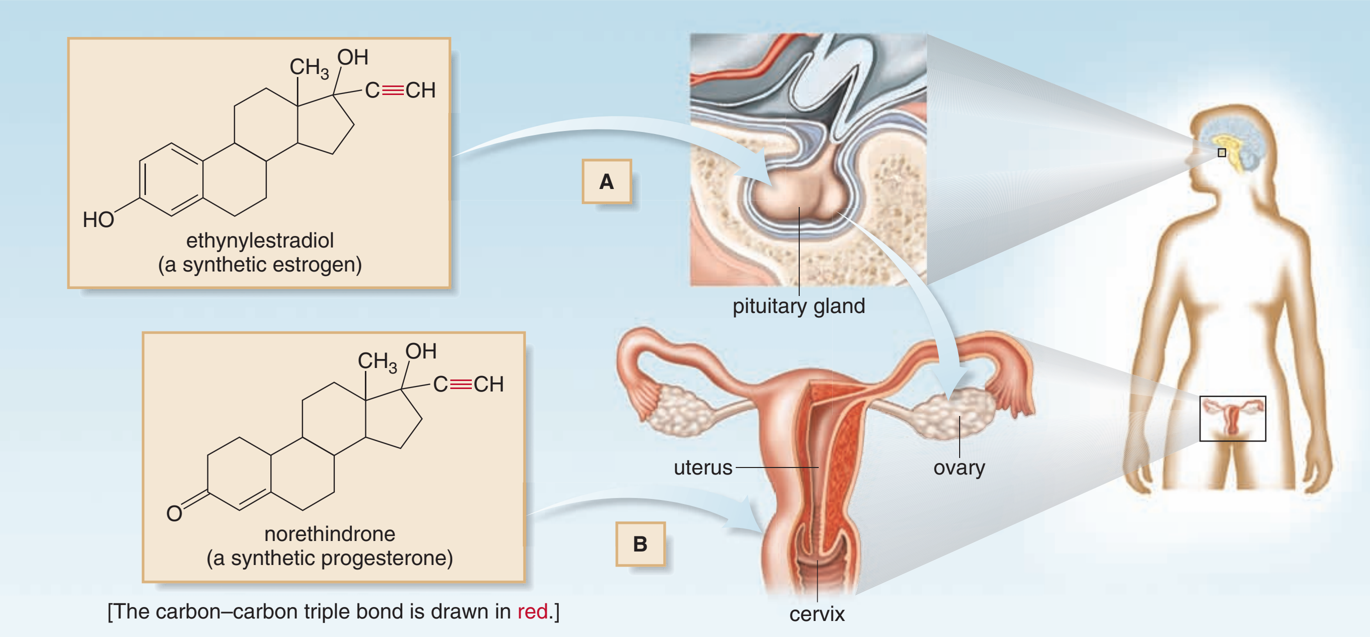
The development of synthetic oral contraceptives in the 1960s revolutionized the ability to control fertility. Prior to that time, women ingested all sorts of substances—iron rust, gunpowder, tree bark, sheep's urine, elephant dung, and others—in the hope of preventing pregnancy.

Synthetic birth control pills are similar in structure to the female sex hormones **estradiol** and **progesterone,** but they also contain a carbon–carbon triple bond. Most oral contraceptives contain two synthetic hormones that are more potent than these natural hormones, so they can be administered in lower doses.



estradiol progesterone

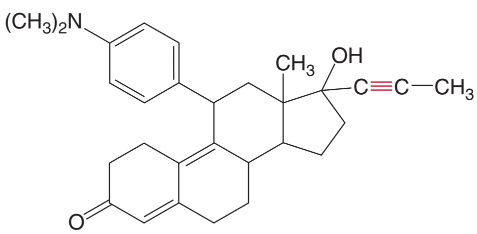
FIGURE 13.3 How Oral Contraceptives Work



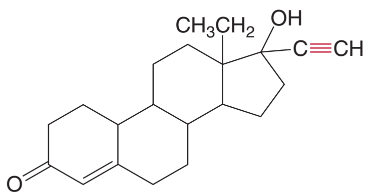
Monthly cycles of hormones from the pituitary gland cause ovulation, the release of an egg from an ovary. To prevent pregnancy, the two synthetic hormones in many oral contraceptives have different effects on the female reproductive system. **A:** The elevated level of **ethynylestradiol,** a synthetic estrogen, "fools" the pituitary gland into thinking a woman is pregnant, so ovulation does not occur. **B:** The elevated level of **norethindrone,** a synthetic progesterone, stimulates the formation of a thick layer of mucus in the cervix, making it difficult for sperm to reach the uterus.

Two common components of birth control pills are **ethynylestradiol** and **norethindrone.** Ethynylestradiol is a synthetic estrogen that resembles the structure and biological activity of estradiol. Norethindrone is a synthetic progesterone that is similar to the natural hormone progesterone. These compounds act by artificially elevating hormone levels in a woman, and this prevents pregnancy, as illustrated in Figure 13.3.

Two other synthetic hormones with triple bonds are **RU 486** and **levonorgestrel.** RU 486 blocks the effects of progesterone, and by this means, prevents implantation of a fertilized egg. RU 486 is used to induce abortions within the first few weeks of pregnancy. Levonorgestrel interferes with ovulation, and thereby prevents pregnancy if taken within a few days of unprotected sex.



RU 486
(Trade name: Mifepristone)



levonorgestrel
(Trade name: Plan B)

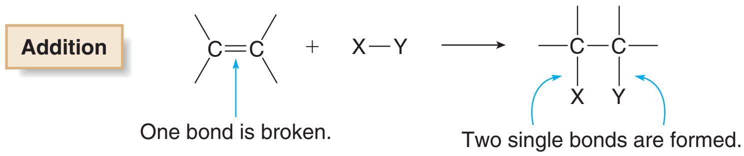
[The carbon–carbon triple bond is drawn in red.]

PROBLEM 13.16 Identify the functional groups in RU 486 and levonorgestrel.

13.6 REACTIONS OF ALKENES

Most families of organic compounds undergo a characteristic type of reaction. **Alkenes undergo addition reactions.** In an addition reaction, new groups X and Y are added to a starting material. One bond of the double bond is broken and two new single bonds are formed.

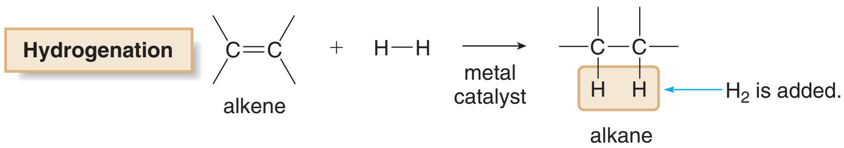
- **Addition is a reaction in which elements are added to a compound.**



Why does addition occur? A double bond is composed of one strong bond and one weak bond. In an addition reaction, the weak bond is broken and two new strong single bonds are formed. Alkenes react with hydrogen (H_2), halogens (Cl_2 and Br_2), hydrogen halides (HCl and HBr), and water (H_2O). These reactions are illustrated in Figure 13.4 with a single alkene starting material.

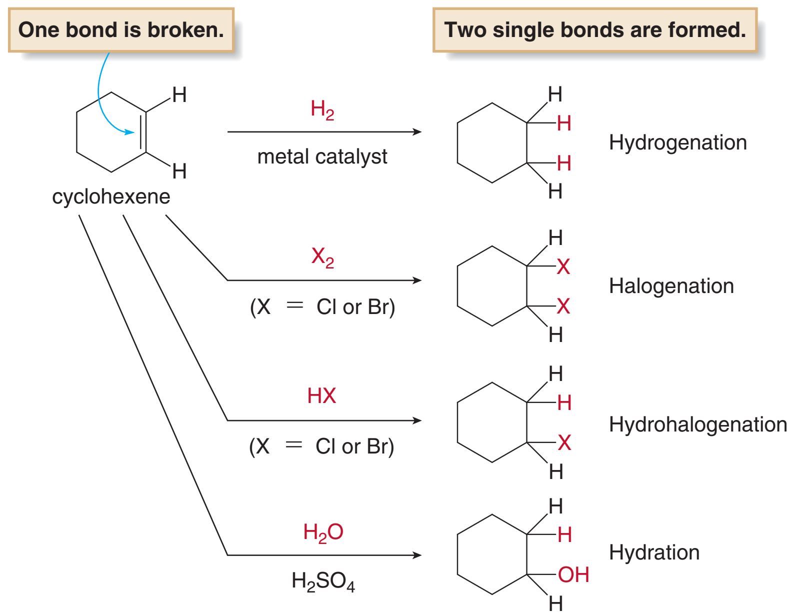
13.6A ADDITION OF HYDROGEN—HYDROGENATION

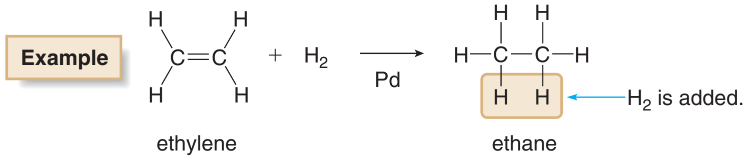
Hydrogenation is the addition of hydrogen (H_2) to an alkene. Two bonds are broken—one bond of the carbon–carbon double bond and the H—H bond—and two new C—H bonds are formed.



The addition of H_2 occurs only in the presence of a **metal catalyst** such as palladium (Pd). The metal provides a surface that binds both the alkene and H_2, and this speeds up the rate of reaction. Hydrogenation of an alkene forms an **alkane** since the product has only C—C single bonds.

FIGURE 13.4 Four Addition Reactions of Alkenes





SAMPLE PROBLEM 13.5

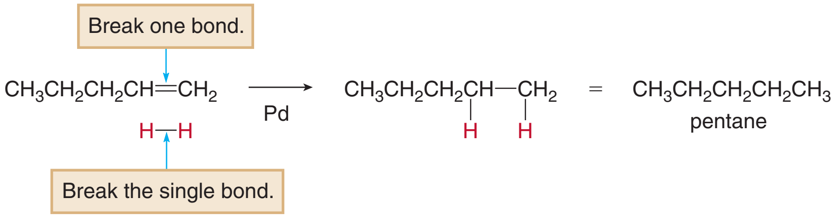
Draw the product of the following reaction.

$$CH_3CH_2CH_2CH{=}CH_2 + H_2 \xrightarrow{Pd}$$

ANALYSIS To draw the product of a hydrogenation reaction:

- Locate the C=C and mentally break one bond in the double bond.
- Mentally break the H—H bond of the reagent.
- Add one H atom to each C of the C=C, thereby forming two new C—H single bonds.

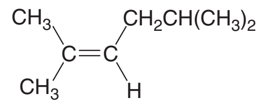
SOLUTION

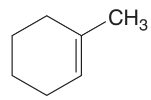


PROBLEM 13.17

What product is formed when each alkene is treated with H_2 and a Pd catalyst?

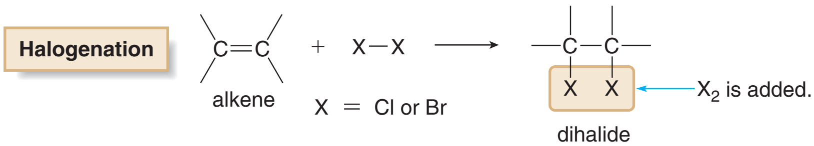
a. $CH_3CH_2CH{=}CHCH_2CH_3$

b. 

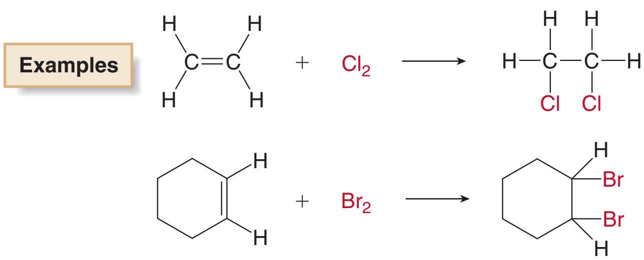
c. 

13.6B ADDITION OF HALOGEN—HALOGENATION

Halogenation is the addition of halogen (X_2) to an alkene. Two bonds are broken—one bond of the carbon–carbon double bond and the X—X bond—and two new C—X bonds are formed.



Halogenation readily occurs with Cl_2 and Br_2. The product of halogenation is a **dihalide.**





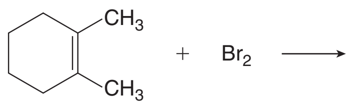
When an alkene is treated with red liquid bromine, the Br_2 adds to the carbon–carbon double bond to give a colorless product.

Halogenation with bromine is a simple chemical test used to determine if a double bond is present in an unknown compound. Bromine is a fuming red liquid. When bromine is added to an alkene, the bromine adds to the double bond and the red color disappears. The disappearance of the red color shows that a double bond is present.

PROBLEM 13.18 Draw the product of each reaction.

a. $CH_3CH_2CH{=}CH_2 + Cl_2 \longrightarrow$

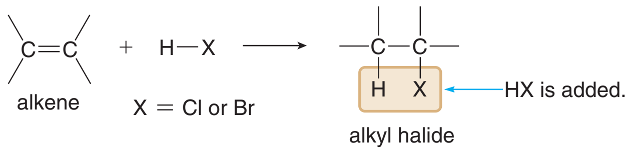
b.



13.6C ADDITION OF HYDROGEN HALIDES—HYDROHALOGENATION

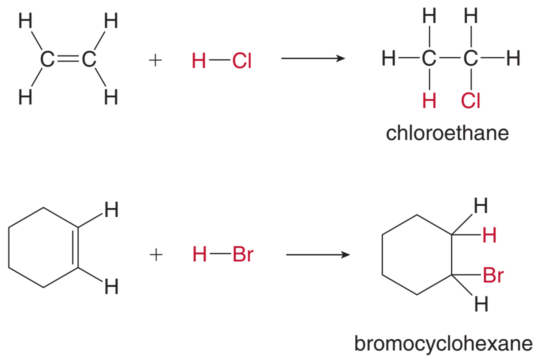
Hydrohalogenation is the addition of HX (X = Cl or Br) to an alkene. Two bonds are broken—one bond of the carbon–carbon double bond and the H—X bond—and new C—H and C—X bonds are formed.

Hydrohalogenation

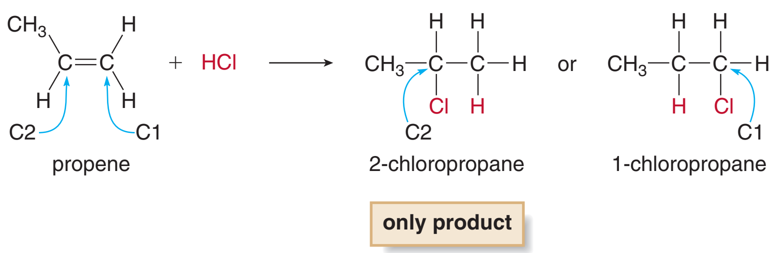


Hydrohalogenation readily occurs with HCl and HBr. The product of hydrohalogenation is an **alkyl halide.**

Examples



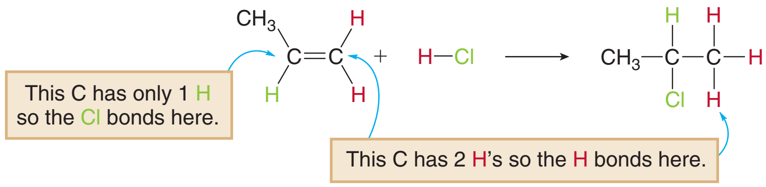
There is one important difference in this addition reaction compared to the addition of H_2 and X_2. In this case, addition puts different atoms—H and X—on the two carbons of the double bond. As a result, HX can add to the double bond to give two constitutional isomers when an unsymmetrical alkene is used as starting material.



For example, the addition of HCl to propene could in theory form two products. If H adds to the end carbon (labeled C1) and Cl adds to the middle carbon (C2), 2-chloropropane is formed. If Cl adds to the end carbon (C1) and H adds to the middle carbon (C2), 1-chloropropane is formed. In fact, **addition forms *only* 2-chloropropane.** This is a specific example of a general trend called **Markovnikov's rule,** named for the Russian chemist who first determined the selectivity of the addition of HX to an alkene.

- **In the addition of HX to an unsymmetrical alkene, the H atom bonds to the less substituted carbon atom—that is, the carbon that has more H's to begin with.**

The end carbon (C1) of propene has two hydrogens while the middle carbon (C2) has just one hydrogen. Addition puts the H of HCl on C1 since it had more hydrogens (two versus one) to begin with.

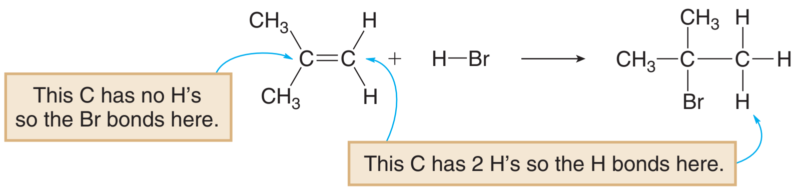


SAMPLE PROBLEM 13.6

What product is formed when 2-methylpropene [$(CH_3)_2C{=}CH_2$] is treated with HBr?

ANALYSIS Alkenes undergo addition reactions, so the elements of H and Br must be added to the double bond. Since the alkene is unsymmetrical, the H atom of HBr bonds to the carbon that has more H's to begin with.

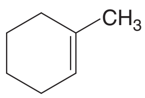
SOLUTION



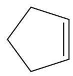
PROBLEM 13.19

What product is formed in each of the following reactions?

a. $CH_3CH{=}CHCH_3$ + HBr ⟶

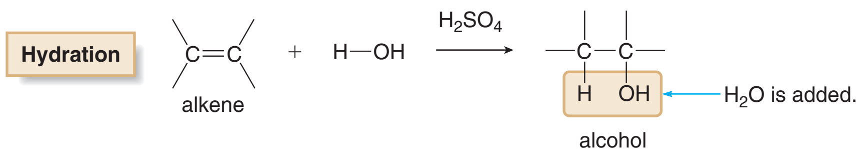
b.  + HBr ⟶

c. $(CH_3)_2C{=}CHCH_3$ + HCl ⟶

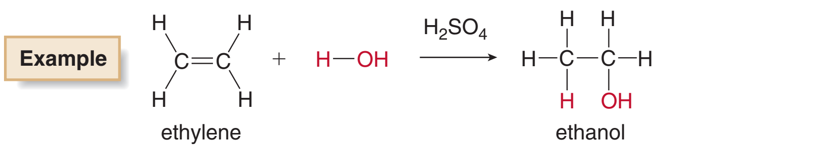
d.  + HCl ⟶

13.6D ADDITION OF WATER—HYDRATION

Hydration is the addition of water to an alkene. Two bonds are broken—one bond of the carbon–carbon double bond and the H—OH bond—and new C—H and C—OH bonds are formed.



Hydration occurs only if a strong acid such as H_2SO_4 is added to the reaction mixture. The product of hydration is an **alcohol.** For example, hydration of ethylene forms ethanol.



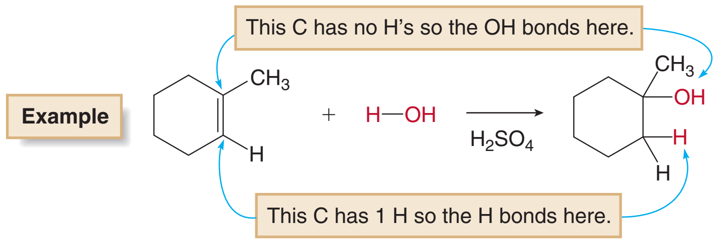


Gasohol contains 10% ethanol.

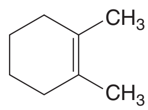
Ethanol is used as a solvent in many reactions in the laboratory. **Ethanol is also used as a gasoline additive** because, like alkanes, it burns in the presence of oxygen to form CO_2 and H_2O with the release of a great deal of energy. Although ethanol can also be formed by the fermentation of carbohydrates in grains and potatoes, much of the ethanol currently used in gasoline and solvent comes from the hydration of ethylene.

The hydration of unsymmetrical alkenes follows Markovnikov's rule.

- **In the addition of H_2O to an unsymmetrical alkene, the H atom bonds to the less substituted carbon atom—that is, the carbon that has more H's to begin with.**



PROBLEM 13.20 What alcohol is formed when each alkene is treated with H_2O in the presence of H_2SO_4?

a. $CH_3CH{=}CHCH_3$
b. $CH_3CH_2CH{=}CH_2$
c. 

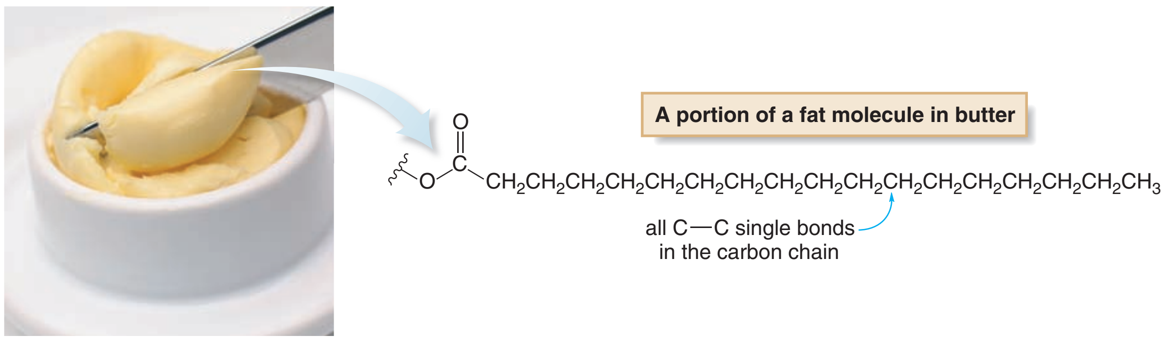
PROBLEM 13.21 What product is formed when 1-pentene ($CH_3CH_2CH_2CH{=}CH_2$) is treated with each reagent?

a. H_2, Pd
b. Cl_2
c. Br_2
d. HBr
e. HCl
f. H_2O, H_2SO_4

13.7 FOCUS ON HEALTH & MEDICINE MARGARINE OR BUTTER?

One addition reaction of alkenes, hydrogenation, is especially important in the food industry. It lies at the heart of the debate over which product, butter or margarine, is better for the consumer.

As we learned in Section 13.3, butter is derived from saturated fatty acids like stearic acid [$CH_3(CH_2)_{16}COOH$], compounds with long carbon chains that contain only carbon–carbon single bonds. As a result, butter is a solid at room temperature.

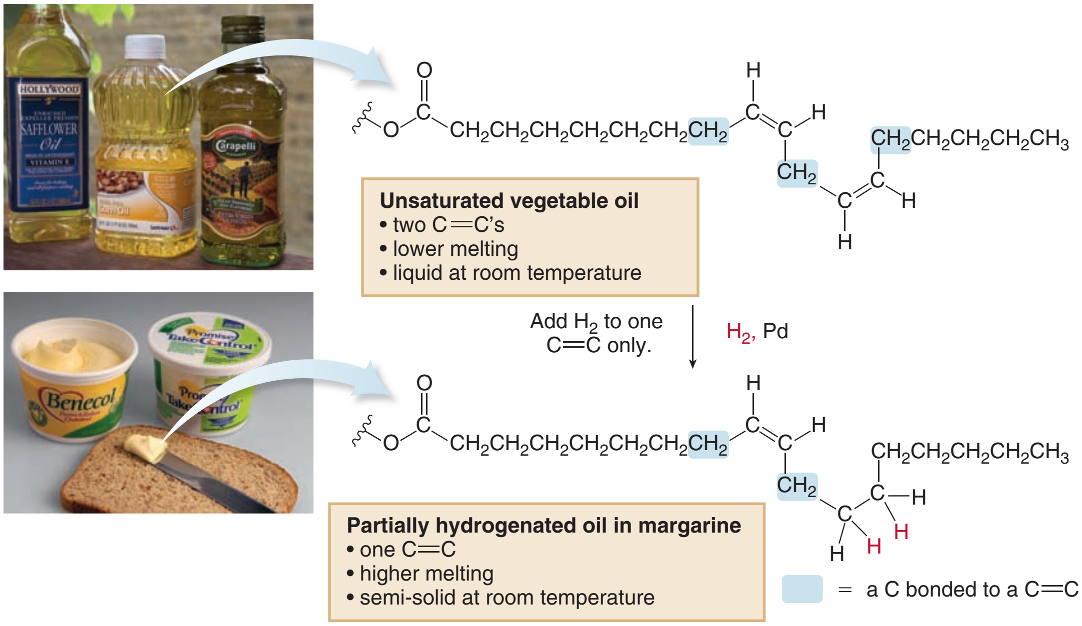


Margarine, on the other hand, is a synthetic product that mimics the taste and texture of butter. It is prepared from vegetable oils derived from unsaturated fatty acids like linoleic acid [$CH_3(CH_2)_4CH{=}CHCH_2CH{=}CH(CH_2)_7COOH$]. Margarine is composed mainly of *partially hydrogenated* vegetable oils formed by adding hydrogen to the double bonds in the carbon chain derived from unsaturated fatty acids.

CONSUMER NOTE

Margarine produced by the partial hydrogenation of vegetable oil has no color or taste. Several ingredients are added to make margarine more closely resemble butter: orange β-carotene (Section 11.7) is often added for color, salt for flavor, and 2,3-butanedione ($CH_3COCOCH_3$) to mimic the flavor of butter.

FIGURE 13.5 Partial Hydrogenation of the Double Bonds in a Vegetable Oil



- When an oil is *partially* hydrogenated, some double bonds react with H_2, while some double bonds remain in the product. Since the product has fewer double bonds, it has a higher melting point. Thus, a liquid oil is converted to a semi-solid.
- Partial hydrogenation decreases the number of carbons bonded to double bonds, making the molecule less easily oxidized, thereby increasing its shelf life.

CONSUMER NOTE



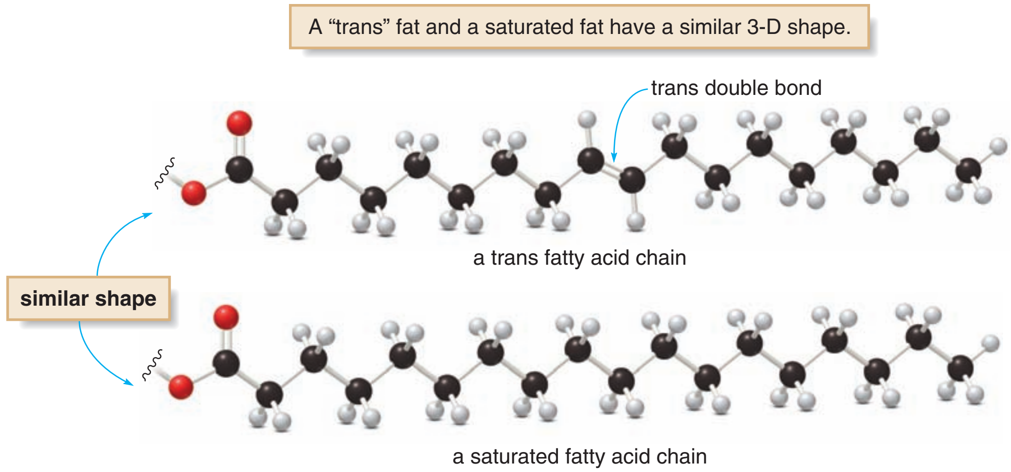
Peanut butter is a common consumer product that contains partially hydrogenated vegetable oil.

When an unsaturated liquid vegetable oil is treated with hydrogen, some (or all) of the double bonds add H_2, as shown in Figure 13.5. This increases the melting point of the oil, thus giving it a semi-solid consistency that more closely resembles butter. This process is called ***hardening.***

As we will learn in Section 19.4, unsaturated oils with carbon–carbon double bonds are healthier than saturated fats with no double bonds. Why, then, does the food industry partially hydrogenate oils, thus reducing the number of double bonds? The reasons relate to texture and shelf life. Consumers prefer the semi-solid consistency of margarine to a liquid oil. Imagine pouring vegetable oil on a piece of toast or pancakes!

Furthermore, unsaturated oils are more susceptible than saturated fats to oxidation at the carbons adjacent to the double bond carbons. Oxidation makes the oil rancid and inedible. Hydrogenating the double bonds reduces the number of carbons bonded to double bonds (also illustrated in Figure 13.5), thus reducing the likelihood of oxidation and increasing the shelf life of the food product. This process reflects a delicate balance between providing consumers with healthier food products, while maximizing shelf life to prevent spoilage.

One other fact is worthy of note. During hydrogenation, some of the cis double bonds in vegetable oils are converted to trans double bonds, forming so-called "trans fats." The shape of the resulting fatty acid chain is very different, closely resembling the shape of a *saturated* fatty acid chain. As a result, trans fats are thought to have the same negative effects on blood cholesterol levels as saturated fats; that is, trans fats stimulate cholesterol synthesis in the liver, thus increasing blood cholesterol levels, a factor linked to increased risk of heart disease.



Which should you choose—butter or margarine—and if it's margarine, which of the many varieties is best for you? Margarine can be hard or soft. It can be made from olive oil, corn oil, safflower oil, or even yogurt. One fact remains clear to nutritionists. It is best to limit your intake of both butter (high in saturated fat) and margarine (high in trans fat).

PROBLEM 13.22

(a) When linolenic acid (Table 13.1) is partially hydrogenated with one equivalent of H_2 in the presence of a Pd catalyst, three constitutional isomers are formed. One of them is linoleic acid. Draw the structures of the other two possible products. (b) What product is formed when linolenic acid is completely hydrogenated with three equivalents of H_2?

PROBLEM 13.23

Draw the structure of a stereoisomer of linoleic acid (Table 13.1) that has two trans double bonds. Which compound would you predict to have the higher melting point? Explain your reasoning.

13.8 POLYMERS—THE FABRIC OF MODERN SOCIETY

***Polymers* are large molecules made up of repeating units of smaller molecules—called *monomers*—covalently bonded together.** Polymers include the naturally occurring proteins that compose hair, tendons, and fingernails. They also include such industrially important plastics as polyethylene, poly(vinyl chloride) (PVC), and polystyrene. Since 1976, the U.S. production of synthetic polymers has exceeded its steel production.

13.8A SYNTHETIC POLYMERS

Many synthetic polymers—that is, those synthesized in the lab—are among the most widely used organic compounds in modern society. Soft drink bottles, plastic bags, food wrap, compact discs, Teflon, and Styrofoam are all made of synthetic polymers. Figure 13.6 illustrates several consumer products and the polymers from which they are made.

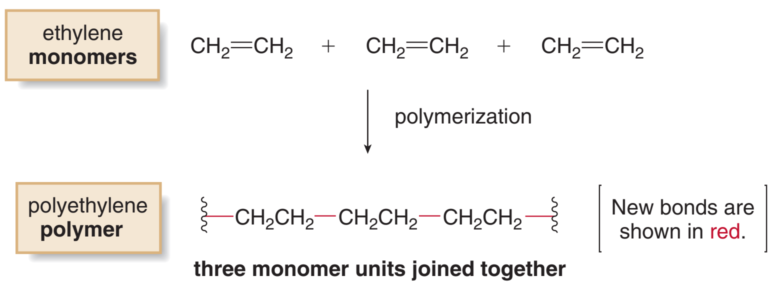
To form a polymer from an alkene monomer, the weak bond that joins the two carbons of the double bond is broken and new strong carbon–carbon single bonds join the monomers together. For example, joining **ethylene monomers** together forms the polymer **polyethylene,** a plastic used in milk containers and sandwich bags.

FIGURE 13.6 Polymers in Some Common Products



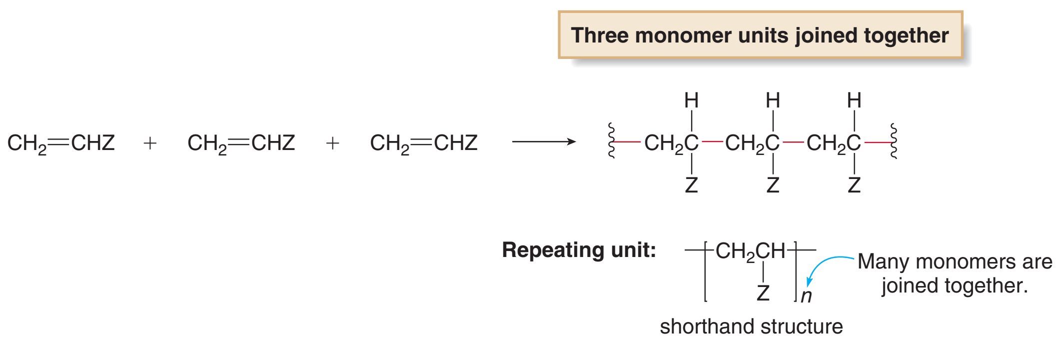


HDPE (high-density polyethylene) and **LDPE** (low-density polyethylene) are common types of polyethylene prepared under different reaction conditions and having different physical properties. HDPE is opaque and rigid, and used in milk containers and water jugs. LDPE is less opaque and more flexible, and used in plastic bags and electrical insulation.



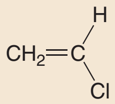
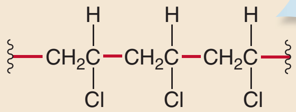
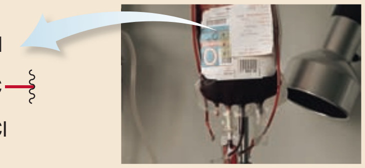
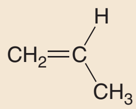
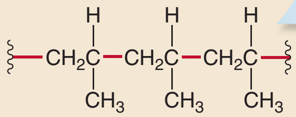
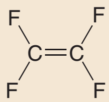
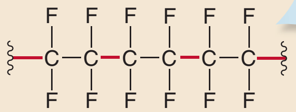
- ***Polymerization*** **is the joining together of monomers to make polymers.**

Many ethylene derivatives having the general structure **$CH_2{=}CHZ$** are also used as monomers for polymerization. The identity of Z affects the physical properties of the resulting polymer, making some polymers more suitable for one consumer product (e.g., plastic bags or food wrap) than another (e.g., soft drink bottles or compact discs). Polymerization of $CH_2{=}CHZ$ usually yields polymers with the Z groups on every other carbon atom in the chain.



Polymer structures are often abbreviated by placing the atoms in the repeating unit in brackets, as shown. Table 13.2 lists some common monomers and polymers used in medicine.

TABLE 13.2 Common Monomers and Polymers Used in Medicine

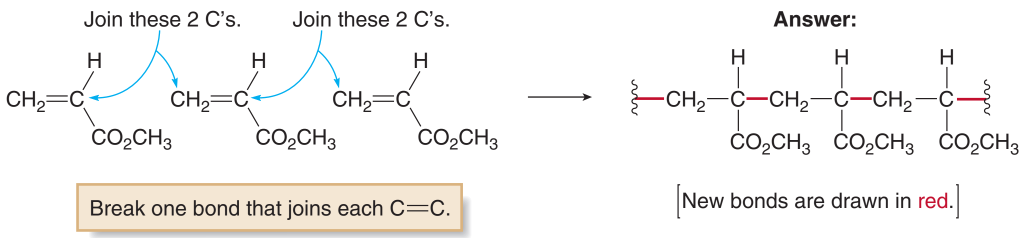
Monomer →	Polymer	Product
 vinyl chloride	 poly(vinyl chloride) PVC	 PVC blood bags and tubing
 propene	 polypropylene	 polypropylene syringes
 tetrafluoroethylene	 polytetrafluoroethylene Teflon	 dental floss

SAMPLE PROBLEM 13.7

What polymer is formed when $CH_2{=}CHCO_2CH_3$ (methyl acrylate) is polymerized?

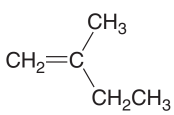
ANALYSIS Draw three or more alkene molecules and arrange the carbons of the double bonds next to each other. Break one bond of each double bond, and join the alkenes together with single bonds. With unsymmetrical alkenes, substituents are bonded to every other carbon.

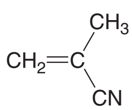
SOLUTION

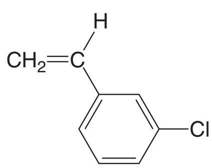


PROBLEM 13.24

What polymer is formed when each compound is polymerized?

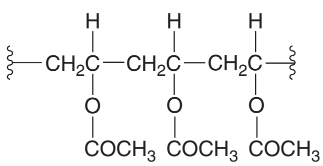
a. 

b. 

c. 

PROBLEM 13.25

What monomer is used to form poly(vinyl acetate), a polymer used in paints and adhesives?



poly(vinyl acetate)

13.8B FOCUS ON THE ENVIRONMENT POLYMER RECYCLING

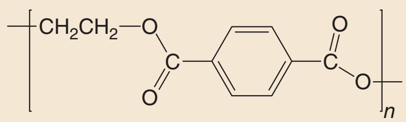
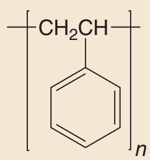
The same desirable characteristics that make polymers popular materials for consumer products—durability, strength, and lack of reactivity—also contribute to environmental problems. Polymers do not degrade readily, and as a result, billions of pounds of polymers end up in landfills every year. Estimates suggest that synthetic polymers comprise 11% of solid municipal waste, 30% of which comes from packaging materials. Recycling existing polymer types to make new materials is one solution to the waste problem created by polymers.

Although thousands of different synthetic polymers have now been prepared, six compounds, called the **"Big Six,"** account for 76% of the synthetic polymers produced in the U.S. each year. Each polymer is assigned a recycling code (1–6) that indicates its ease of recycling; **the lower the number, the easier it is to recycle.** Table 13.3 lists these six most common polymers, as well as the type of products made from each recycled polymer.

Recycling begins with sorting plastics by type, shredding into small chips, and washing to remove adhesives and labels. After drying and removing any metal caps or rings, the polymer is melted and molded for reuse.

Of the Big Six, only the polyethylene terephthalate (PET) in soft drink bottles and the high-density polyethylene (HDPE) in milk jugs and juice bottles are recycled to any great extent. Since recycled polymers are often still contaminated with small amounts of adhesives and other materials, these recycled polymers are generally not used for storing food or drink products. Recycled HDPE is converted to Tyvek, an insulating wrap used in new housing construction, and recycled PET is used to make fibers for fleece clothing and carpeting. Currently about 23% of all plastics are recycled in the U.S.

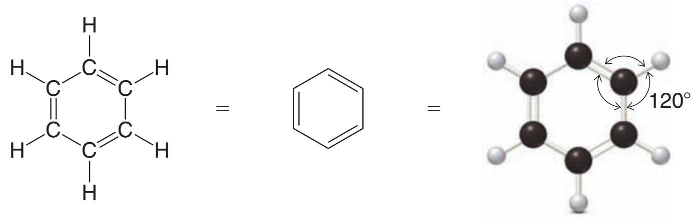
TABLE 13.3 Recyclable Polymers

Recycling Code	Polymer Name	Shorthand Structure	Recycled Product
1	PET polyethylene terephthalate		fleece jackets carpeting plastic bottles
2	HDPE high-density polyethylene	$\text{-}[CH_2CH_2]_n\text{-}$	Tyvek insulation sports clothing
3	PVC poly(vinyl chloride)	$\text{-}[CH_2CH(Cl)]_n\text{-}$	floor mats
4	LDPE low-density polyethylene	$\text{-}[CH_2CH_2]_n\text{-}$	trash bags
5	PP polypropylene	$\text{-}[CH_2CH(CH_3)]_n\text{-}$	furniture
6	PS polystyrene		molded trays trash cans

13.9 AROMATIC COMPOUNDS

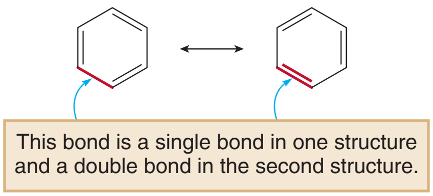
Aromatic compounds represent another example of unsaturated hydrocarbons. Aromatic compounds were originally named because many simple compounds in this family have characteristic odors. Today, the word **aromatic refers to compounds that contain a benzene ring,** or rings that react in a similar fashion to benzene.

Benzene, the simplest and most widely known aromatic compound, contains a six-membered ring and three double bonds. Since each carbon of the ring is also bonded to a hydrogen atom, the molecular formula for benzene is C_6H_6. Each carbon is surrounded by three groups, making it trigonal planar. Thus, **benzene is a planar molecule,** and all bond angles are **120°.**



benzene C_6H_6 planar molecule

Although benzene is drawn with a six-membered ring and three double bonds, there are two different ways to arrange the double bonds so that they alternate with single bonds around the ring.



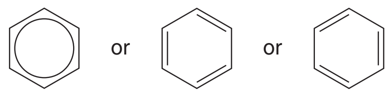
Drawing resonance structures was first presented in Section 4.4.

Each of these representations has the same arrangement of atoms. Only the location of the electrons is different. These structures are called **resonance structures.**

- **Resonance structures are Lewis structures with the same arrangement of atoms but a different arrangement of electrons.**

A **double-headed arrow** indicates that the two structures are resonance structures. In actuality, neither structure represents the true structure of benzene. The true structure of benzene is really a combination of both resonance structures, called a **hybrid.** Because the electron pair in a given double bond in a benzene ring is not really located between two particular carbon atoms, we say that the three electron pairs in the double bonds are *delocalized* in the six-membered ring. This gives benzene added stability compared to other unsaturated hydrocarbons.

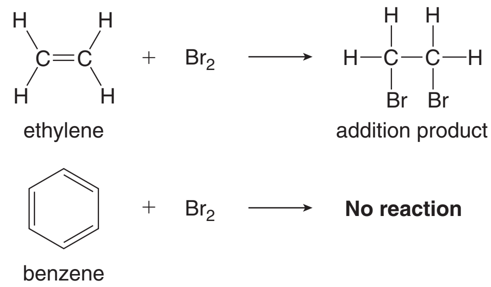
Sometimes, a benzene ring is drawn with a circle inside a hexagon in place of the three double bonds.



three equivalent representations of benzene

The circle is meant to show that the six electrons from the three double bonds move freely around the ring. Realize, however, that we can draw benzene using either resonance structure or a benzene ring with a circle inside. Each of these representations is equivalent.

The physical properties of aromatic hydrocarbons are similar to other hydrocarbons—they have low melting points and boiling points and are water insoluble. Their chemical properties, however, are very different. **Aromatic hydrocarbons do not undergo the addition reactions that characterize alkenes.** For example, bromine adds to ethylene to form an addition product with two new C—Br bonds, but benzene does not react under similar conditions.



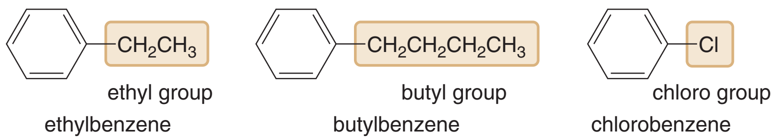
- **Aromatic compounds resemble benzene—they are unsaturated compounds that do not undergo the addition reactions characteristic of alkenes.**

13.10 NOMENCLATURE OF BENZENE DERIVATIVES

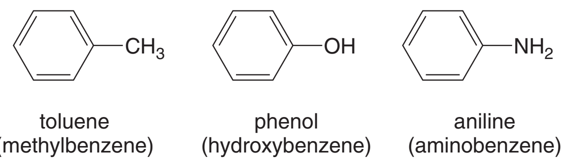
Many organic molecules contain a benzene ring with one or more substituents, so we must learn how to name them. Many common names are recognized by the IUPAC system, however, so this complicates the nomenclature of benzene derivatives somewhat.

13.10A MONOSUBSTITUTED BENZENES

To name a benzene ring with one substituent, **name the substituent and add the word *benzene*.** Carbon substituents are named as alkyl groups. When a halogen is a substituent, name the halogen by changing the *-ine* ending of the name of the halogen to the suffix *-o*; for example, chlor***ine*** → chlor***o***.



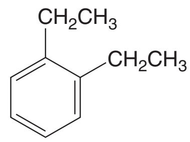
Many monosubstituted benzenes, such as those with methyl (CH_3–), hydroxyl (–OH), and amino (–NH_2) groups, have common names that you must learn, too.



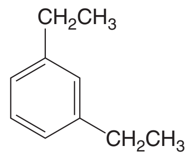
13.10B DISUBSTITUTED BENZENES

There are three different ways that two groups can be attached to a benzene ring, so a prefix—**ortho, meta,** or **para**—is used to designate the relative position of the two substituents. Ortho, meta, and para are also abbreviated as ***o, m,*** and ***p,*** respectively.

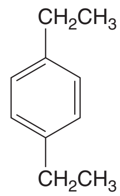
1,2-Disubstituted benzene **ortho** isomer	**1,3**-Disubstituted benzene **meta** isomer	**1,4**-Disubstituted benzene **para** isomer



ortho-diethylbenzene
or
o-diethylbenzene
or
1,2-diethylbenzene



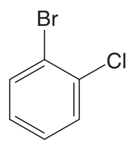
meta-diethylbenzene
or
m-diethylbenzene
or
1,3-diethylbenzene



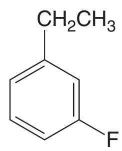
para-diethylbenzene
or
p-diethylbenzene
or
1,4-diethylbenzene

If the two groups on the benzene ring are different, **alphabetize the name of the substituents** preceding the word benzene. If one of the substituents is part of a **common root,** name the **molecule as a derivative of that monosubstituted benzene.**

Alphabetize two different substituent names:

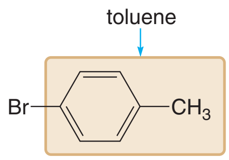


o-**b**romo**c**hloro-benzene

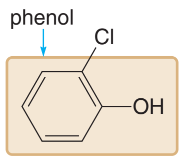


m-**e**thyl**f**luoro-benzene

Use a common root name:



p-bromo**toluene**



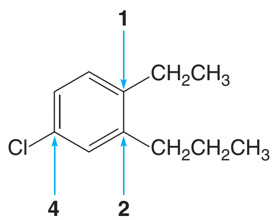
o-chloro**phenol**

13.10C POLYSUBSTITUTED BENZENES

For three or more substituents on a benzene ring:

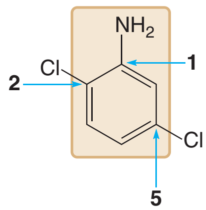
1. **Number to give the lowest possible numbers around the ring.**
2. **Alphabetize the substituent names.**
3. **When substituents are part of common roots, name the molecule as a derivative of that monosubstituted benzene. The substituent that comprises the common root is located at C1, but the "1" is omitted from the name.**

Examples of naming polysubstituted benzenes



- Assign the lowest set of numbers.
- Alphabetize the names of all the substituents.

4-**c**hloro-**1**-**e**thyl-**2**-**p**ropylbenzene

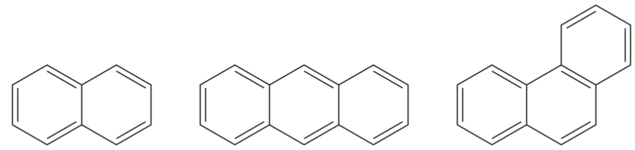


- Name the molecule as a derivative of the common root **aniline.**
- Designate the position of the NH_2 group as "1," and then assign the lowest possible set of numbers to the other substituents.

2,5-dichloro**aniline**

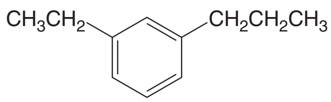
13.10D AROMATIC COMPOUNDS WITH MORE THAN ONE RING

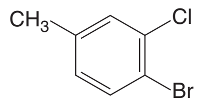
Some aromatic compounds contain two or more benzene rings joined together. Naphthalene has two benzene rings joined together. There are two different aromatic hydrocarbons with three benzene rings, named anthracene and phenanthrene.



naphthalene anthracene phenanthrene

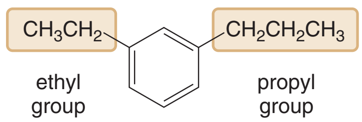
SAMPLE PROBLEM 13.8 Name each of the following aromatic compounds.

a. 

b. 

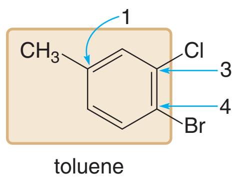
ANALYSIS Name the substituents on the benzene ring. With two groups, alphabetize the substituent names and use the prefix ortho, meta, or para to indicate their location. With three substituents, alphabetize the substituent names, and number to give the lowest set of numbers.

SOLUTION

a. 

- The two substituents are located 1,3- or **meta** to each other.
- Alphabetize the *e* of **e**thyl before the *p* of **p**ropyl.

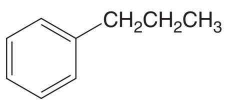
Answer: *m*-ethylpropylbenzene

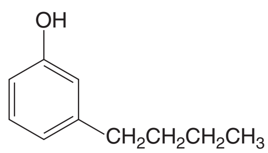
b. 

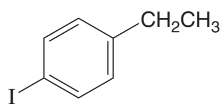
- Since a CH_3– group is bonded to the ring, name the molecule as a derivative of toluene.
- Place the CH_3 group at the "1" position, and number to give the lowest set of numbers.

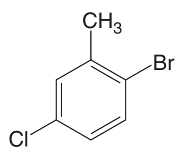
Answer: 4-bromo-3-chlorotoluene

PROBLEM 13.26 Give the IUPAC name of each compound.

a. 

c. 

b. 

d. 

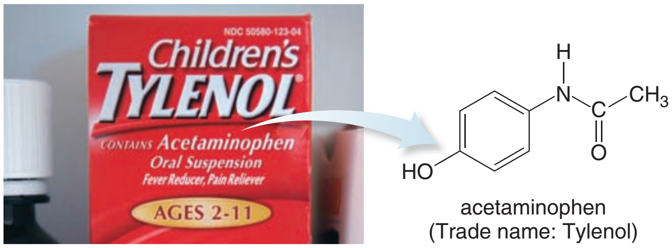
PROBLEM 13.27 Draw the structure corresponding to each name.

a. pentylbenzene
b. *o*-dichlorobenzene
c. *m*-bromoaniline
d. 4-chloro-1,2-diethylbenzene

13.11 FOCUS ON HEALTH & MEDICINE AROMATIC DRUGS, SUNSCREENS, AND CARCINOGENS

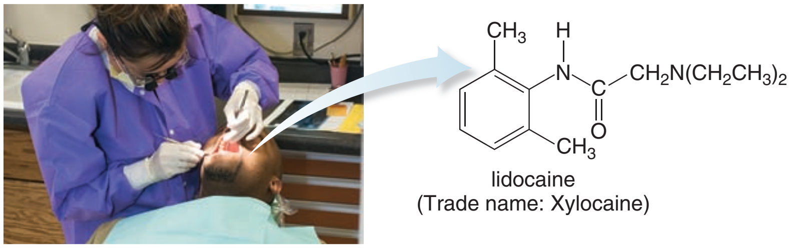
Many widely used drugs contain an aromatic ring. Notable examples include the analgesic acetaminophen, the local anesthetic lidocaine, and the antihistamine loratadine (Figure 13.7). These drugs are better known by their trade names Tylenol, Xylocaine, and Claritin, respectively.

FIGURE 13.7 Three Drugs That Contain a Benzene Ring



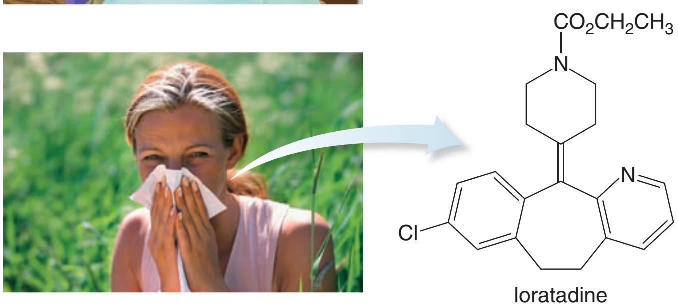
acetaminophen
(Trade name: Tylenol)

- Acetaminophen reduces fever and pain, but it is not anti-inflammatory. Thus, it is ineffective in treating conditions like arthritis, which have a significant inflammatory component.



lidocaine
(Trade name: Xylocaine)

- Lidocaine is a local anesthetic used to numb the skin when suturing an injury. It is also commonly used by dentists.



loratadine
(Trade name: Claritin)

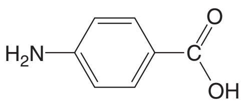
- Loratadine is an over-the-counter antihistamine used for the treatment of seasonal allergies. Loratadine is an antihistamine that does not cause drowsiness.

HEALTH NOTE

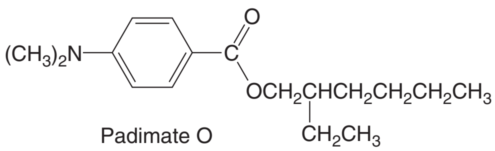


Commercial sunscreens are given an **SPF** rating (sun protection factor), according to the amount of sunscreen present. The higher the number, the greater the protection.

All commercially available sunscreens contain a benzene ring. A sunscreen absorbs ultraviolet radiation and thus shields the skin for a time from its harmful effects. Two sunscreens that have been used for this purpose are *p*-aminobenzoic acid (PABA) and Padimate O.



p-aminobenzoic acid
(PABA)



Padimate O

Compounds containing two or more benzene rings that share carbon–carbon bonds are called **polycyclic aromatic hydrocarbons (PAHs). Benzo[*a*]pyrene,** a PAH containing five rings joined together, is a widespread environmental pollutant, produced during the combustion of all types of organic material—gasoline, fuel oil, wood, garbage, and cigarettes.



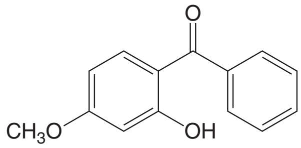
tobacco plant

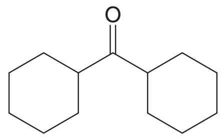
benzo[*a*]pyrene
(a polycyclic aromatic hydrocarbon)

When benzo[*a*]pyrene, a nonpolar and water-insoluble hydrocarbon, is inhaled or ingested, it is oxidized in the liver. Oxidation is a common fate of foreign substances that are not useful nutrients for the body. The oxidation products are more polar, making them much more water soluble, and more readily excreted in urine. The oxidation product from benzo[*a*]pyrene is also a potent **carcinogen;** that is, it causes cancer. The carcinogen binds to a needed protein or DNA in the cell and disrupts normal cell function, causing cancer or cell death.

PROBLEM 13.28

Which of the following compounds might be an ingredient in a commercial sunscreen? Explain why or why not.

a. 

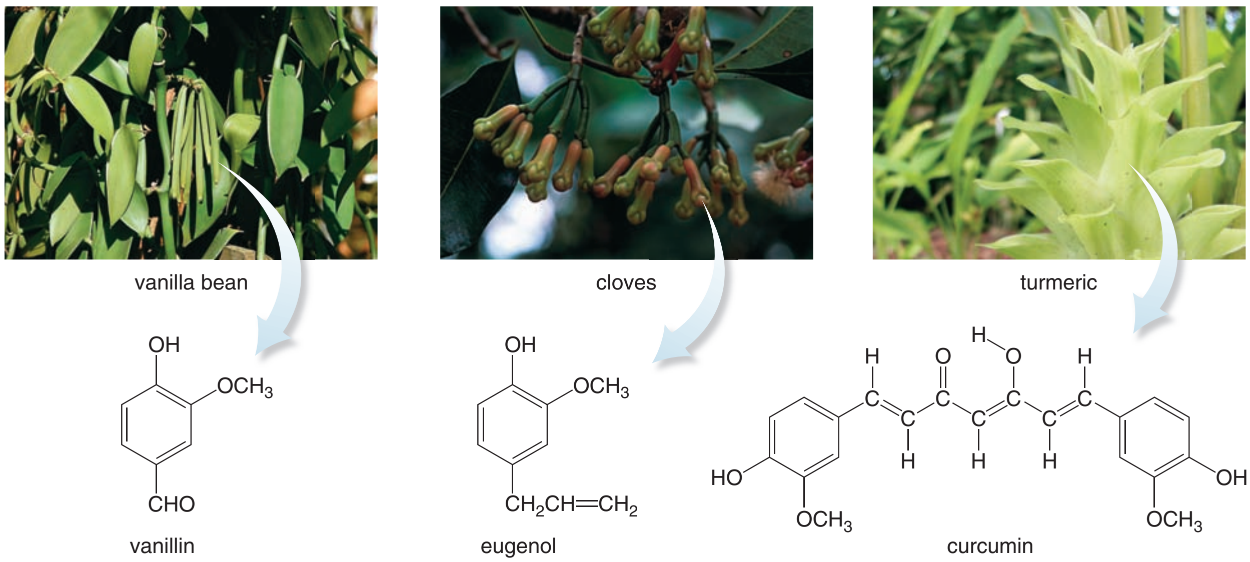
b. 

PROBLEM 13.29

What oxidation products are formed when benzo[*a*]pyrene is completely combusted (see Section 12.8)?

13.12 FOCUS ON HEALTH & MEDICINE PHENOLS AS ANTIOXIDANTS

A wide variety of phenols, compounds that contain a hydroxyl group bonded to a benzene ring, occur in nature. **Vanillin** from the vanilla bean and **eugenol** from cloves are both phenols.



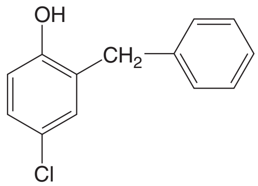
Curcumin is a yellow pigment isolated from turmeric, a tropical perennial in the ginger family and a principal ingredient in curry powder. Curcumin has long been used as an anti-inflammatory agent in traditional eastern medicine. In some preliminary research carried out with mice, curcumin was shown to correct the defect that causes cystic fibrosis, a fatal genetic disease that afflicts 30,000 children and young adults in the United States.

Some phenols are antiseptics and others are irritants. The disinfectant Lysol contains 2-benzyl-4-chlorophenol. The phenol urushiol in poison ivy causes an irritating rash on contact.

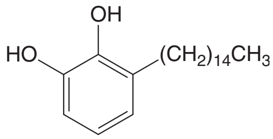
HEALTH NOTE



Nuts are an excellent source of vitamin E.

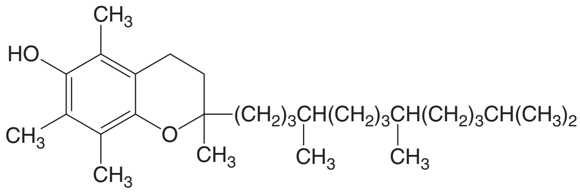


2-benzyl-4-chlorophenol
(active ingredient in Lysol)

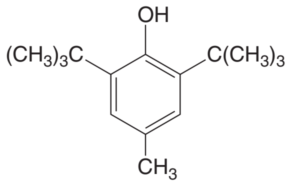


urushiol
(found in poison ivy)

Like lycopene (Section 13.4), many **phenols are antioxidants.** Two examples are naturally occurring vitamin E and synthetic BHT. **The OH group on the benzene ring is the key functional group that prevents unwanted oxidation reactions from occurring.**



vitamin E



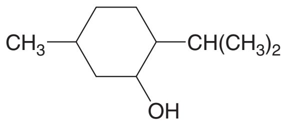
BHT
(**b**utylated **h**ydroxy **t**oluene)

Vitamin E is a natural antioxidant found in fish oil, peanut oil, wheat germ, and leafy greens. Although the molecular details of its function remain obscure, it is thought that vitamin E prevents the unwanted oxidation of unsaturated fatty acid residues in cell membranes. In this way, vitamin E helps retard the aging process.

Synthetic antioxidants such as **BHT**—**b**utylated **h**ydroxy **t**oluene—are added to packaged and prepared foods to prevent oxidation and spoilage. BHT is a common additive in breakfast cereals.

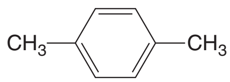
PROBLEM 13.30

Which of the following compounds might be antioxidants?

a. 

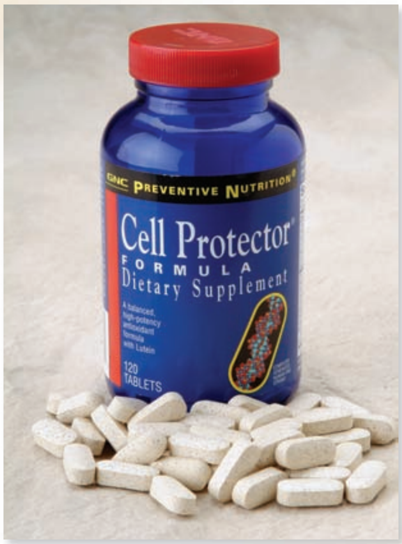
menthol

b. curcumin

c. 

p-xylene
(gasoline additive)

HEALTH NOTE

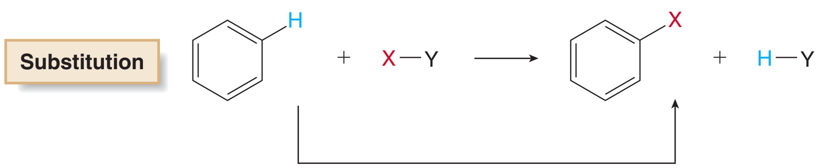


The purported health benefits of antioxidants have made them a popular component in anti-aging formulations.

13.13 REACTIONS OF AROMATIC COMPOUNDS

Like the alkenes, aromatic compounds undergo a characteristic type of reaction. In contrast to the alkenes, however, aromatic compounds undergo **substitution** *not* addition.

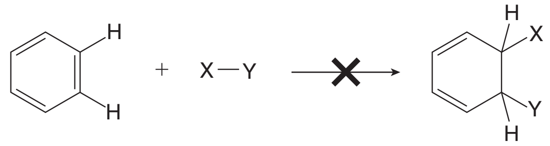
- **Substitution is a reaction in which an atom is *replaced* by another atom or a group of atoms.**



substitution of H by X

Why does substitution occur? **Substitution of H by X keeps the stable aromatic ring intact.** Benzene does *not* undergo addition reactions like other unsaturated hydrocarbons because the product would not contain a benzene ring.

Addition does *not* occur.



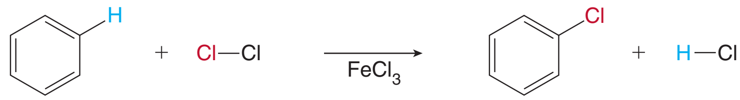
The product is *not* aromatic.

Three specific reactions of benzene are considered: **chlorination, nitration,** and **sulfonation.** In each reaction, one hydrogen atom on the benzene ring is replaced by another atom or group: –Cl, $–NO_2$, or $–SO_3H$, respectively.

13.13A CHLORINATION AND THE SYNTHESIS OF THE PESTICIDE DDT

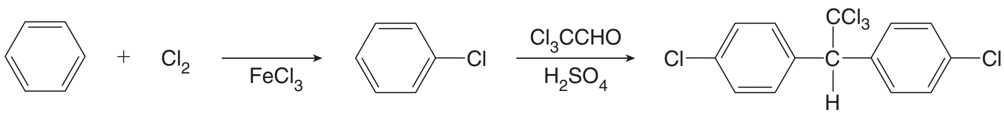
Benzene reacts with Cl_2 in the presence of an iron catalyst ($FeCl_3$) to yield chlorobenzene. Chlorobenzene is an **aryl halide,** an organic halide with the halogen bonded directly to the aromatic ring. Reaction with chlorine is called **chlorination.** In chlorination, a Cl atom substitutes for a hydrogen atom on the benzene ring.

Chlorination



chlorobenzene

The chlorination of benzene is the first step in the two-step synthesis of the pesticide **DDT** (***d****ichloro****d****iphenyl****t****richloroethane*).



DDT
(nonbiodegradable pesticide)

DDT is an organic molecule with valuable short-term effects that has caused long-term problems. DDT kills insects that spread diseases such as malaria and typhus, and in controlling insect populations, DDT has saved millions of lives worldwide. DDT is a weakly polar and very stable organic compound, and so it (and compounds like it) persists in the environment for years. Since DDT is soluble in organic media, it accumulates in the fatty tissues of most animals. Most adults in the U.S. have low concentrations of DDT (or a degradation product of DDT) in them. The long-term effect on humans is not known, but DDT has had a direct harmful effect on the eggshell formation of certain predator birds such as eagles and hawks.

ENVIRONMENTAL NOTE



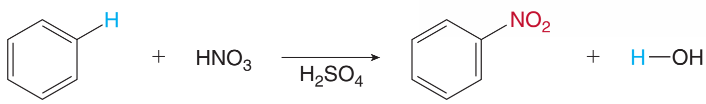
Time Magazine, June 30, 1947.

Winston Churchill called DDT a "miraculous" chemical in 1945 for the many lives it saved during World War II. Less than 20 years later, as prolonged use of large quantities of this nonspecific pesticide led to harmful environmental effects, Rachel Carson called DDT the "elixir of death" in her book *Silent Spring.* DDT use was banned in the U.S. in 1973, but given its low cost, it is still widely used to control insect populations in developing countries.

13.13B FOCUS ON HEALTH & MEDICINE NITRATION AND SULFA DRUGS

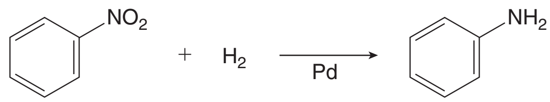
Benzene reacts with nitric acid (HNO_3) in the presence of sulfuric acid (H_2SO_4) to yield nitrobenzene. Substitution of a **nitro group** (NO_2) for a hydrogen is called **nitration.**

Nitration



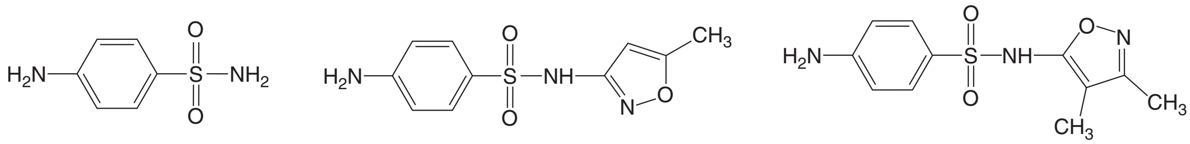
nitrobenzene

Nitration is a very valuable reaction because nitro groups are readily converted to amino groups, (NH_2) with H_2 and a palladium catalyst.



aniline

Many of the antibacterial sulfa drugs have NH_2 groups bonded to the benzene ring. Examples include sulfanilamide, one of the first antibiotics synthesized in the 1930s, and newer sulfa drugs such as sulfamethoxazole (trade name Bactrim) and sulfisoxazole (trade name Gantrisin), which are used to treat ear and urinary tract infections.

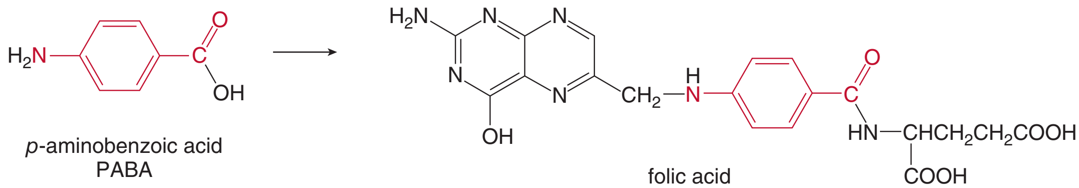


sulfanilamide

sulfamethoxazole (Trade name: Bactrim)

sulfisoxazole (Trade name: Gantrisin)

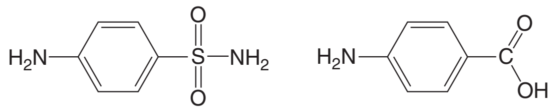
In cells, sulfamethoxazole and sulfisoxazole are both metabolized to sulfanilamide, the active agent. To understand how sulfanilamide functions as an antibacterial agent we must examine **folic acid,** which microorganisms synthesize from *p*-aminobenzoic acid.



p-aminobenzoic acid PABA

folic acid

Sulfanilamide and *p*-aminobenzoic acid are similar in size and shape and have related functional groups. Thus, when sulfanilamide is administered, bacteria attempt to use it in place of *p*-aminobenzoic acid to synthesize folic acid. Derailing folic acid synthesis means that the bacteria cannot grow and reproduce. Sulfanilamide only affects bacterial cells, though, because humans do not synthesize folic acid, and must obtain it from their diets.



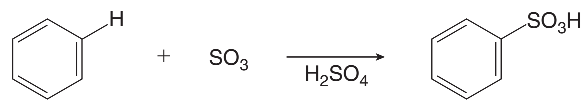
sulfanilamide

p-aminobenzoic acid

13.13C SULFONATION AND DETERGENT SYNTHESIS

Benzene reacts with sulfur trioxide (SO_3) in the presence of sulfuric acid (H_2SO_4) to yield benzenesulfonic acid. Substitution of SO_3H for a hydrogen is called **sulfonation.**

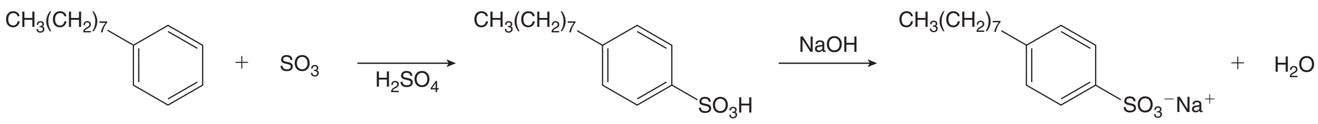
Sulfonation



benzenesulfonic acid

Although less widely used than chlorination and nitration, sulfonation is an important step in the synthesis of detergents. Many detergents are sodium salts of sulfonic acids, and are prepared by the two-step sequence shown in Figure 13.8.

FIGURE 13.8 Synthesis of a Detergent Using Sulfonation



a benzenesulfonic acid

sodium salt of
a benzenesulfonic acid

synthetic detergent

PROBLEM 13.31 What product is formed when *p*-dichlorobenzene is treated with each reagent: (a) Cl_2, $FeCl_3$; (b) HNO_3, H_2SO_4; (c) SO_3, H_2SO_4?

PROBLEM 13.32 When toluene (methylbenzene) is treated with Cl_2 and $FeCl_3$, a total of three products are possible. Draw the structure of the three products and give their IUPAC names.

CHAPTER HIGHLIGHTS

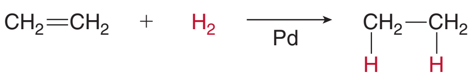
KEY TERMS

Addition reaction (13.6)
Alkene (13.1)
Alkyne (13.1)
Antioxidant (13.4)
Aromatic compound (13.9)
Aryl halide (13.13)
Chlorination (13.13)
Cis isomer (13.3)
Double-headed arrow (13.9)
Fat (13.3)
Fatty acid (13.3)
Halogenation (13.6)
Hardening (13.7)
Hybrid (13.9)
Hydration (13.6)
Hydrogenation (13.6)
Hydrohalogenation (13.6)
Markovnikov's rule (13.6)
Meta isomer (13.10)
Monomer (13.8)
Nitration (13.13)
Nitro group (13.13)
Oil (13.3)
Ortho isomer (13.10)
Para isomer (13.10)
Partial hydrogenation (13.7)
Polycyclic aromatic hydrocarbon (13.11)
Polymer (13.8)
Polymerization (13.8)
Resonance structure (13.9)
Stereoisomer (13.3)
Substitution reaction (13.13)
Sulfonation (13.13)
Trans isomer (13.3)
Unsaturated hydrocarbon (13.1)

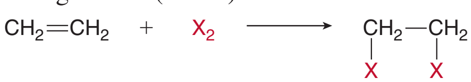
KEY REACTIONS

[1] Addition reactions of alkenes (13.6)

a. Hydrogenation (13.6A)

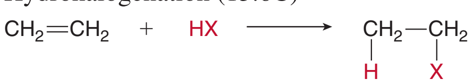


b. Halogenation (13.6B)



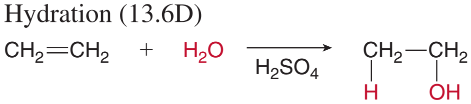
(X = Cl or Br)

c. Hydrohalogenation (13.6C)



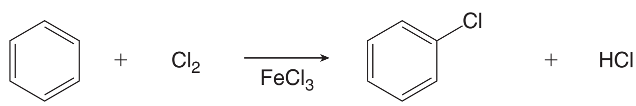
(X = Cl or Br)

d. Hydration (13.6D)

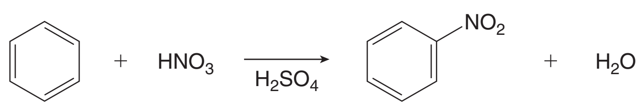


[2] Substitution reactions of benzene (13.13)

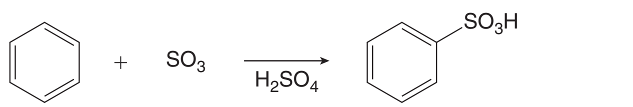
a. Chlorination (13.13A)



b. Nitration (13.13B)



c. Sulfonation (13.13C)



KEY CONCEPTS

1 What are the characteristics of alkenes, alkynes, and aromatic compounds?

- Alkenes are unsaturated hydrocarbons that contain a carbon–carbon double bond and have molecular formula C_nH_{2n}. Each carbon of the double bond is trigonal planar. (13.1)
- Alkynes are unsaturated hydrocarbons that contain a carbon–carbon triple bond and have molecular formula C_nH_{2n-2}. Each carbon of the triple bond is linear. (13.1)
- Benzene, molecular formula C_6H_6, is the most common aromatic hydrocarbon. Benzene is a stable hybrid of two resonance structures, each containing a six-membered ring and three double bonds. Each carbon of benzene is trigonal planar. (13.9)

2 How are alkenes, alkynes, and substituted benzenes named?

- An alkene is identified by the suffix *-ene,* and the carbon chain is numbered to give to the C═C the lower number. (13.2)
- An alkyne is identified by the suffix *-yne,* and the carbon chain is numbered to give to the C≡C the lower number. (13.2)
- Substituted benzenes are named by naming the substituent and adding the word *benzene*. When two substituents are bonded to the ring, the prefixes ortho, meta, and para are used to show the relative positions of the two groups: 1,2-, 1,3- or 1,4-, respectively. With three substituents on a benzene ring, number to give the lowest possible numbers. (13.10)

3 What is the difference between constitutional isomers and stereoisomers? How are cis and trans isomers different? (13.3)

- Constitutional isomers differ in the way the atoms are bonded to each other.
- Stereoisomers differ only in the three-dimensional arrangement of atoms.
- Cis and trans isomers are one type of stereoisomer. A cis alkene has two alkyl groups on the same side of the double bond. A trans alkene has two alkyl groups on opposite sides of the double bond.

4 How do saturated and unsaturated fatty acids differ? (13.3B)

- Fatty acids are carboxylic acids (RCOOH) with long carbon chains. Saturated fatty acids have no double bonds in the carbon chain and unsaturated fatty acids have one or more double bonds in their long carbon chains.
- All double bonds in naturally occurring fatty acids are cis.
- As the number of double bonds in the fatty acid increases, the melting point decreases.

5 What types of reactions do alkenes undergo? (13.6)

- Alkenes undergo addition reactions with reagents X—Y. One bond of the double bond and the X—Y bond break and two new single bonds (C—X and C—Y) are formed.
- Alkenes react with four different reagents—H_2 (Pd catalyst), X_2 (X = Cl or Br), HX (X = Cl or Br), and H_2O (with H_2SO_4).

6 What is Markovnikov's rule? (13.6)

- Markovnikov's rule explains the selectivity observed when an unsymmetrical reagent HX adds to an unsymmetrical alkene like propene ($CH_3CH{=}CH_2$). The H of HX is added to the end of the C═C that has more H's to begin with, forming $CH_3CH(X)CH_3$.

7 What products are formed when a vegetable oil is partially hydrogenated? (13.7)

- When an unsaturated oil is partially hydrogenated, some but not all of the cis C═C's add H_2, reducing the number of double bonds and increasing the melting point.
- Some of the cis double bonds are converted to trans double bonds, forming trans fats, whose shape and properties closely resemble those of saturated fats.

8 What are polymers, and how are they formed from alkene monomers? (13.8)

- Polymers are large molecules made up of repeating smaller molecules called monomers covalently bonded together. When alkenes are polymerized, one bond of the double bond breaks, and two new single bonds join the alkene monomers together in long carbon chains.

9 What types of reactions does benzene undergo? (13.13)

- To keep the stable aromatic ring intact, benzene undergoes substitution, not addition, reactions. One H atom on the ring is replaced by another atom or group of atoms. Reactions include chlorination (substitution by Cl), nitration (substitution by NO_2), and sulfonation (substitution by SO_3H).

PROBLEMS

Selected in-chapter and end-of-chapter problems have brief answers provided in Appendix B.

Alkene, Alkyne, and Benzene Structure

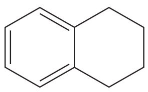
13.33 What is the molecular formula for a hydrocarbon with 10 carbons that is (a) completely saturated; (b) an alkene; (c) an alkyne?

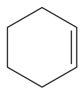
13.34 Draw the structure of a hydrocarbon with molecular formula C_6H_{10} that also contains: (a) a carbon–carbon triple bond; (b) two carbon–carbon double bonds; (c) one ring and one C=C.

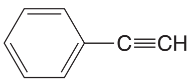
13.35 Draw structures for the three alkynes having molecular formula C_5H_8.

13.36 Draw the structures of the five constitutional isomers of molecular formula C_5H_{10} that contain a double bond.

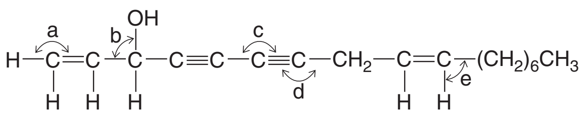
13.37 Label each carbon in the following molecules as tetrahedral, trigonal planar, or linear.

a. 

c. 

b. 

13.38 Falcarinol is a natural pesticide found in carrots that protects them from fungal diseases. Predict the indicated bond angles in falcarinol.

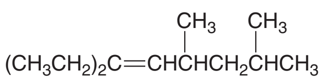


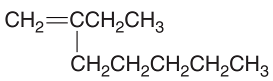
falcarinol

Nomenclature of Alkenes and Alkynes

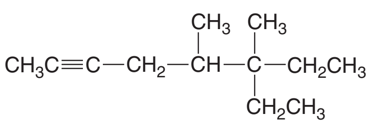
13.39 Give the IUPAC name for each compound.

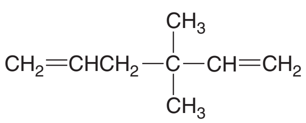
a. $CH_2{=}CHCH_2CH_2C(CH_3)_3$

b. 

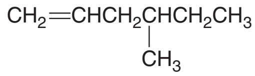
c. 

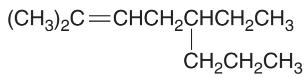
d. $CH_3C{\equiv}CCH_2C(CH_3)_3$

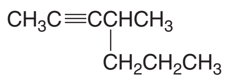
e. 

f. 

13.40 Give the IUPAC name for each compound.

a. 

b. 

c. 

d. $(CH_3)_3CC{\equiv}CC(CH_3)_3$

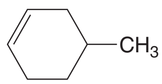
e. $(CH_3CH_2CH_2CH_2)_2C{=}CHCH_3$

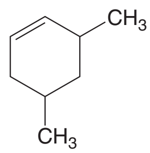
f. $(CH_3)_2C{=}CHCH_2CH_2CH_2CH{=}C(CH_3)_2$

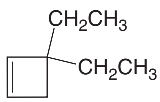
13.41 Give the IUPAC name for each alkyne in Problem 13.35.

13.42 Give the IUPAC name for each alkene in Problem 13.36.

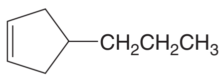
13.43 Give the IUPAC name for each cyclic compound.

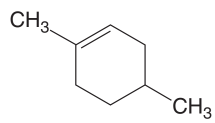
a. 

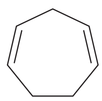
c. 

b. 

13.44 Give the IUPAC name for each cyclic compound.

a. 

c. 

b. 

13.45 Give the structure corresponding to each IUPAC name.

a. 3-methyl-1-octene
b. 1-ethylcyclobutene
c. 2-methyl-3-hexyne
d. 3,5-diethyl-2-methyl-3-heptene
e. 1,3-heptadiene
f. *cis*-7-methyl-2-octene

13.46 Give the structure corresponding to each IUPAC name.

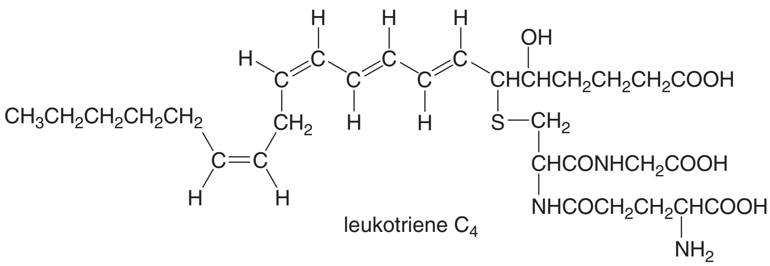
a. 1,2-dimethylcyclopentene
b. 6-ethyl-2-octyne
c. 3,3-dimethyl-1,4-pentadiene
d. *trans*-5-methyl-2-hexene
e. 5,6-dimethyl-2-heptyne
f. 3,4,5,6-tetramethyl-1-decyne

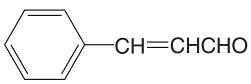
13.47 Each of the following IUPAC names is incorrect. Explain why it is incorrect and give the correct IUPAC name.
a. 5-methyl-4-hexene
b. 1-methylbutene
c. 2,3-dimethylcyclohexene
d. 3-butyl-1-butyne

13.48 Each of the following IUPAC names is incorrect. Explain why it is incorrect and give the correct IUPAC name.
a. *cis*-2-methyl-2-hexene
b. 2-methyl-2,4-pentadiene
c. 2,4-dimethylcyclohexene
d. 1,1-dimethyl-2-cyclohexene

Isomers

13.49 Leukotriene C_4 is a key compound that causes the constriction of small airways, and in this way contributes to the asthmatic response. Label each double bond in leukotriene C_4 as cis or trans.



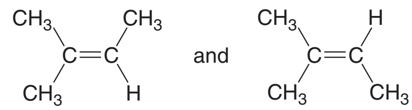
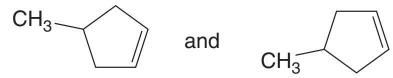
13.50 Draw the complete structure of each naturally occurring compound using the proper cis or trans arrangement around the carbon–carbon double bond. Muscalure is the sex attractant of the housefly. Cinnamaldehyde is responsible for the odor of cinnamon.
a. $CH_3(CH_2)_8CH{=}CH(CH_2)_{12}CH_3$
muscalure
(cis double bond)
b. 
cinnamaldehyde
(trans double bond)

13.51 Draw the cis and trans isomers for each compound: (a) 2-nonene; (b) 2-methyl-3-heptene.

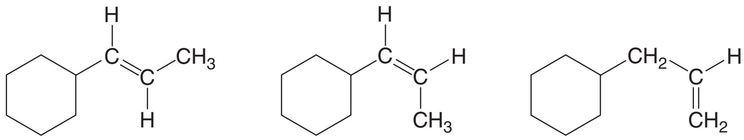
13.52 Draw the cis and trans isomers for each compound: (a) 3-heptene; (b) 4,4-dimethyl-2-hexene.

13.53 Explain the difference between a constitutional isomer and a stereoisomer.

13.54 Draw all of the possible stereoisomers for 2,4-hexadiene ($CH_3CH{=}CH{-}CH{=}CHCH_3$).

13.55 How are the compounds in each pair related? Choose from constitutional isomers, stereoisomers, or identical.
a. $CH_3C{\equiv}CCH_3$ and $HC{\equiv}CCH_2CH_3$
b. 
c. 
d. 

13.56 Consider alkenes **A, B,** and **C.** How are the compounds in each pair related? Choose from constitutional isomers, stereoisomers, or identical: (a) **A** and **B;** (b) **A** and **C;** (c) **B** and **C.**

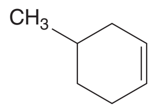
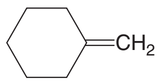


A **B** **C**

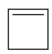
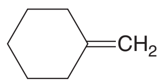
13.57 Why are there no cis and trans isomers when an alkene has two like groups bonded to one end of the double bond?

13.58 Why can't an alkyne have cis and trans isomers?

Reactions of Alkenes

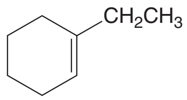
13.59 What alkane is formed when each alkene is treated with H_2 in the presence of a Pd catalyst?
a. $CH_2{=}CHCH_2CH_2CH_2CH_3$
b. $(CH_3)_2C{=}CHCH_2CH_2CH_3$
c. 
d. 

13.60 What dihalide is formed when each of the alkenes in Problem 13.59 is treated with Br_2?

13.61 What alkyl halide is formed when each alkene is treated with HCl?
a. 
b. $(CH_3)_2C{=}C(CH_3)_2$
c. $CH_2{=}CHCH_2CH(CH_3)_2$
d. 

13.62 What alcohol is formed when each alkene in Problem 13.61 is treated with H_2O and H_2SO_4?

13.63 Draw the product formed when 1-ethylcyclohexene is treated with each reagent.

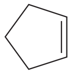


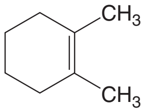
1-ethylcyclohexene

a. H_2, Pd
b. Cl_2
c. Br_2
d. HCl
e. HBr
f. H_2O, H_2SO_4

13.64 Draw the products formed in each reaction.

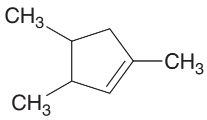
a. $CH_3CH{=}CHCH_3$ + HCl ⟶

b.  + H_2 $\xrightarrow{\text{Pd}}$

c.  + Cl_2 ⟶

d. $CH_3CH{=}CHCH_2CH_2CH_3$ + Br_2 ⟶

e. $(CH_3)_2C{=}CHCH_2CH_3$ + HBr ⟶

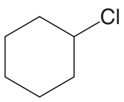
f.  + H_2O $\xrightarrow{H_2SO_4}$

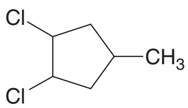
13.65 The hydration of 2-pentene ($CH_3CH{=}CHCH_2CH_3$) with H_2O and H_2SO_4 forms two alcohols. Draw the structure of both products and explain why more than one product is formed.

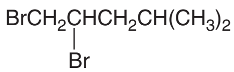
13.66 When myrcene (Problem 13.2) is treated with three equivalents of H_2O in the presence of H_2SO_4, a single addition product of molecular formula $C_{10}H_{22}O_3$ is formed. Keeping Markovnikov's rule in mind, draw the product.

13.67 What alkene is needed as a starting material to prepare each of the following alkyl halides or dihalides. In each case, also indicate what reagent is needed to react with the alkene.

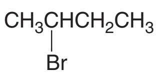
a. CH_3CH_2Br

b. 

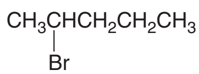
c. 

d. 

13.68 2-Bromobutane can be formed as the only product of the addition of HBr to two different alkenes. In contrast, 2-bromopentane can be formed as the *only* product of the addition of HBr to just one alkene. Draw the structures of the alkene starting materials and explain the observed results.

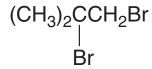
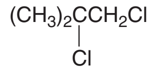


2-bromobutane

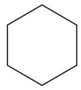
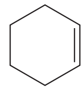


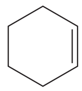
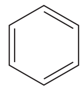
2-bromopentane

13.69 What reagent is needed to convert 2-methylpropene [$(CH_3)_2C{=}CH_2$] to each compound?

a. $(CH_3)_3CCl$
b. $(CH_3)_3CH$
c. $(CH_3)_3COH$
d. $(CH_3)_3CBr$
e. 
f. 

13.70 What chemical test can be used to distinguish between each pair of compounds? Describe what you would visually observe (color changes or no changes in color) for each compound.

a.  and 

b.  and 

Polymers

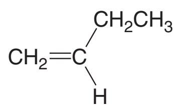
13.71 What is the difference between a polymer and a monomer?

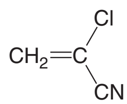
13.72 What is the difference between HDPE and LDPE?

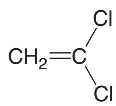
13.73 Draw the structure of poly(acrylic acid), the polymer formed by polymerizing acrylic acid ($CH_2{=}CHCOOH$). Poly(acrylic acid) is used in disposable diapers because it can absorb 30 times its weight in water.

13.74 What polymer is formed when methyl α-methylacrylate [$CH_2{=}C(CH_3)CO_2CH_3$] is polymerized? This polymer is used in Lucite and Plexiglas, transparent materials that are lighter but more impact resistant than glass.

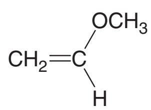
13.75 What polymer is formed when each compound is polymerized?

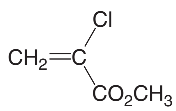
a. 

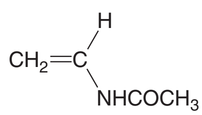
b. 

c. 

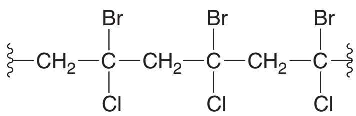
13.76 What polymer is formed when each compound is polymerized?

a. 

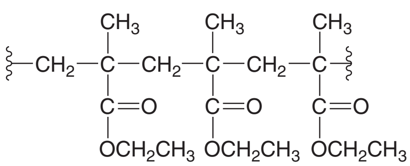
b. 

c. 

13.77 What monomer is used to form the following polymer?



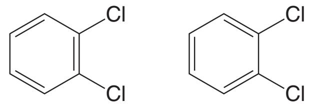
13.78 What monomer is used to form the following polymer?



Structure and Nomenclature of Benzene

13.79 Draw two resonance structures for chlorobenzene.

13.80 Explain why structures **A** and **B** are the same compound, even though **A** has the two Cl atoms on the same double bond and **B** has the two Cl atoms on different double bonds.

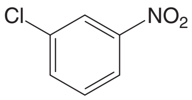


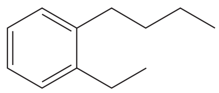
A **B**

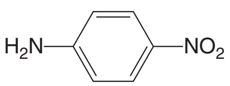
13.81 What is the difference between a resonance structure and an isomer?

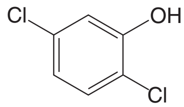
13.82 What is the difference between a resonance structure and a hybrid?

13.83 Give the IUPAC name for each substituted benzene.

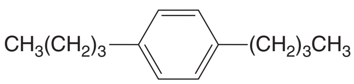
a. 

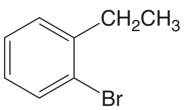
c. 

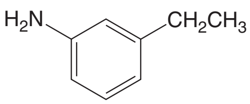
b. 

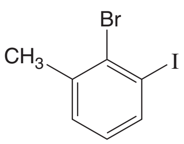
d. 

13.84 Give the IUPAC name for each substituted benzene.

a. 

b. 

c. 

d. 

13.85 Draw the structure of the three constitutional isomers that have a Cl atom and an NH_2 group bonded to a benzene ring. Name each compound using the IUPAC system.

13.86 Draw the structure of TNT, the explosive that has the IUPAC name 2,4,6-trinitrotoluene.

13.87 Give the structure corresponding to each IUPAC name.

a. *p*-nitropropylbenzene
b. *m*-dibutylbenzene
c. *o*-iodophenol
d. 2-bromo-4-chlorotoluene
e. 2-chloro-6-iodoaniline

13.88 Give the structure corresponding to each IUPAC name.

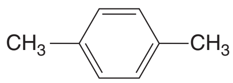
a. *m*-ethylnitrobenzene
b. *o*-difluorobenzene
c. *p*-bromotoluene
d. 1,3,5-trinitrobenzene
e. 2,4-dibromophenol

13.89 Each of the following IUPAC names is incorrect. Explain why it is incorrect and give the correct IUPAC name: (a) 5,6-dichlorophenol; (b) *m*-dibromoaniline.

13.90 Each of the following IUPAC names is incorrect. Explain why it is incorrect and give the correct IUPAC name: (a) 1,5-dichlorobenzene; (b) 1,3-dibromotoluene.

Reactions of Aromatic Compounds

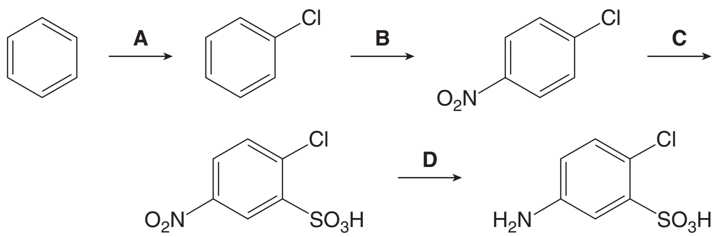
13.91 What product is formed when *p*-dimethylbenzene (also called *p*-xylene) is treated with each reagent?



p-dimethylbenzene

a. Cl_2, $FeCl_3$
b. HNO_3, H_2SO_4
c. SO_3, H_2SO_4

13.92 What reagents (**A–D**) are needed to carry out each reaction in the following sequence?



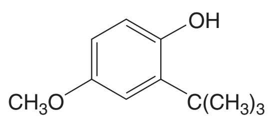
13.93 When bromobenzene is treated with HNO_3 and H_2SO_4, three different products are formed. Draw the structures of the three products formed.

13.94 You have three bottles (labeled **A, B,** and **C**) and each contains one of the *o*-, *m*-, or *p*-dibromobenzene isomers, but you don't know which isomer is in which bottle. When the dibromobenzene isomer in bottle **A** is treated with Cl_2 and $FeCl_3$, one product of molecular formula $C_6H_3Br_2Cl$ is obtained. When the dibromobenzene isomer in bottle **B** is treated with Cl_2 and $FeCl_3$, three products of molecular formula $C_6H_3Br_2Cl$ are obtained. When the dibromobenzene isomer in bottle **C** is treated with Cl_2 and $FeCl_3$, two products of molecular formula $C_6H_3Br_2Cl$ are obtained. Which isomer (ortho, meta, or para) is contained in which bottle (**A, B,** or **C**)?

Applications

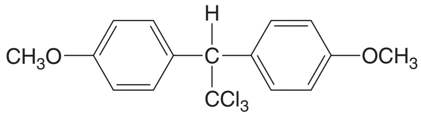
13.95 The breakfast cereal Cheerios lists vitamin E as one of its ingredients. What function does vitamin E serve?

13.96 Why is BHA an ingredient in some breakfast cereals and other packaged foods?



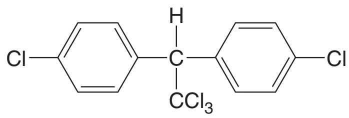
BHA
(**b**utylated **h**ydroxy **a**nisole)

13.97 Although nonpolar compounds tend to dissolve and remain in fatty tissues, polar substances are more water soluble, and more readily excreted into an environment where they may be degraded by other organisms. Explain why methoxychlor is more biodegradable than DDT.

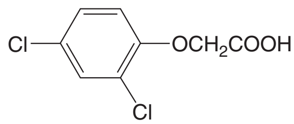


methoxychlor

13.98 Explain why the pesticide DDT is insoluble in water, but the herbicide 2,4-D is water soluble. 2,4-D is one component of the defoliant Agent Orange used extensively during the Vietnam War.



DDT



2,4-D

13.99 Kukui nuts contain oil that is high in linoleic acid content (Table 13.1). (a) What two constitutional isomers are formed when linoleic acid is partially hydrogenated with one equivalent of H_2? (b) What product is formed when linoleic acid is completely hydrogenated with H_2? (c) What product would be formed if, during hydrogenation, one equivalent of H_2 is added, *and* one of the cis double bonds is converted to a trans double bond?

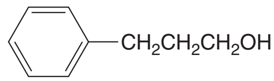
13.100 Eleostearic acid is an unsaturated fatty acid found in tung oil, obtained from the seeds of the tung oil tree (*Aleurites fordii*), a deciduous tree native to China. Eleostearic acid is unusual in that the double bond at C9 is cis, but the other two double bonds are trans. (a) Draw the structure of eleostearic acid, showing the arrangement of groups around each double bond. (b) Draw a stereoisomer of eleostearic acid in which all of the double bonds are trans. (c) Which compound, eleostearic acid or its all-trans isomer, has the higher melting point? Explain your reasoning.

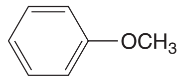
$$CH_3(CH_2)_3CH{=}CHCH{=}CHCH{=}CH(CH_2)_7CO_2H$$

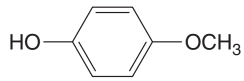
(C9)

eleostearic acid

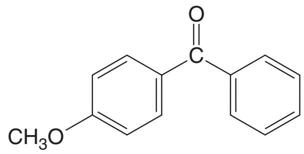
13.101 Which of the following compounds might be an antioxidant?

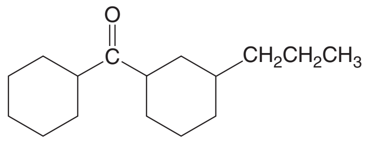
a. 

b. 

c. 

13.102 Which of the following compounds might be an ingredient in a commercial sunscreen?

a. 

b. 

13.103 When benzene enters the body, it is oxidized to phenol (C_6H_5OH). What is the purpose of this oxidation reaction?

13.104 Explain what a PAH is, and give an example of a PAH mentioned in this chapter, other than benzo[*a*]pyrene.

13.105 Macadamia nuts have a high concentration of unsaturated oils formed from palmitoleic acid [$CH_3(CH_2)_5CH{=}CH(CH_2)_7COOH$]. (a) Draw the structure of the naturally occurring fatty acid with a cis double bond. (b) Draw a stereoisomer of palmitoleic acid. (c) Draw a constitutional isomer of palmitoleic acid.

13.106 What products are formed when polyethylene is completely combusted?

General Questions

13.107 Explain the difference between a substitution reaction and an addition reaction.

13.108 What is the difference between a phenol and an alcohol? Give an example of each compound.

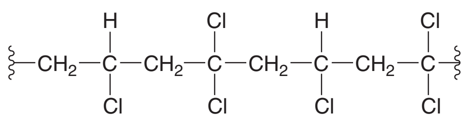
13.109 Why is the six-membered ring in benzene flat but the six-membered ring in cyclohexane is puckered (not flat)?

13.110 Explain why *p*-dichlorobenzene is a nonpolar molecule but *o*-dichlorobenzene is a polar molecule.

CHALLENGE QUESTIONS

13.111 Are *cis*-2-hexene and *trans*-3-hexene constitutional isomers or stereoisomers? Explain.

13.112 Some polymers are copolymers, formed from two different alkene monomers joined together. An example is Saran, the polymer used in the well known plastic food wrap. What two alkene monomers combine to form Saran?



Saran

14

CHAPTER OUTLINE

CHAPTER GOALS

In this chapter you will learn how to:

1. Identify alcohols, ethers, alkyl halides, and thiols
2. Classify alcohols and alkyl halides as 1°, 2°, or 3°
3. Determine the properties of alcohols, ethers, alkyl halides, and thiols
4. Name alcohols, ethers, alkyl halides, and thiols
5. Draw the products of the dehydration of alcohols
6. Determine the products of alcohol oxidation
7. Convert thiols to disulfides



Ethanol, the alcohol in wine, beer, and other alcoholic beverages, is formed by the fermentation of carbohydrates in grapes, grains, and potatoes.

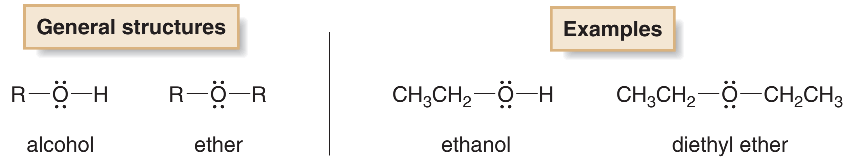
ORGANIC COMPOUNDS THAT CONTAIN OXYGEN, HALOGEN, OR SULFUR

CHAPTER 14 concentrates on four families of organic compounds that contain a carbon singly bonded to a heteroatom—**alcohols** (ROH), **ethers** (ROR), **alkyl halides** (RX, X = F, Cl, Br, or I), and **thiols** (RSH). The polar carbon–heteroatom bond gives these compounds different properties than the hydrocarbons of Chapters 12 and 13. Of the four families, alcohols are the most widely occurring, represented by simple compounds such as ethanol (CH_3CH_2OH) and by complex compounds such as starch and cellulose. Ethers are the most common anesthetics in use today, and alkyl halides, widely used as industrial solvents and refrigerants, are responsible for the destruction of the ozone layer. The –SH group of thiols plays an important role in protein chemistry. In Chapter 14, we learn about the properties of these four groups of organic compounds.

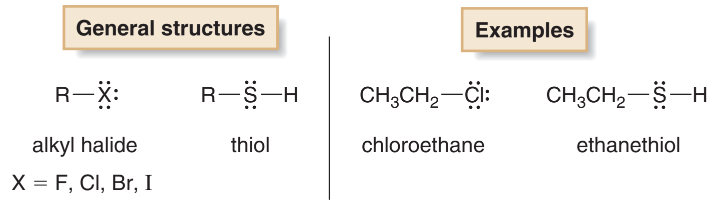
14.1 INTRODUCTION

Alcohols, ethers, alkyl halides, and **thiols** are four families of compounds that contain a carbon atom singly bonded to a heteroatom—oxygen, halogen, or sulfur.

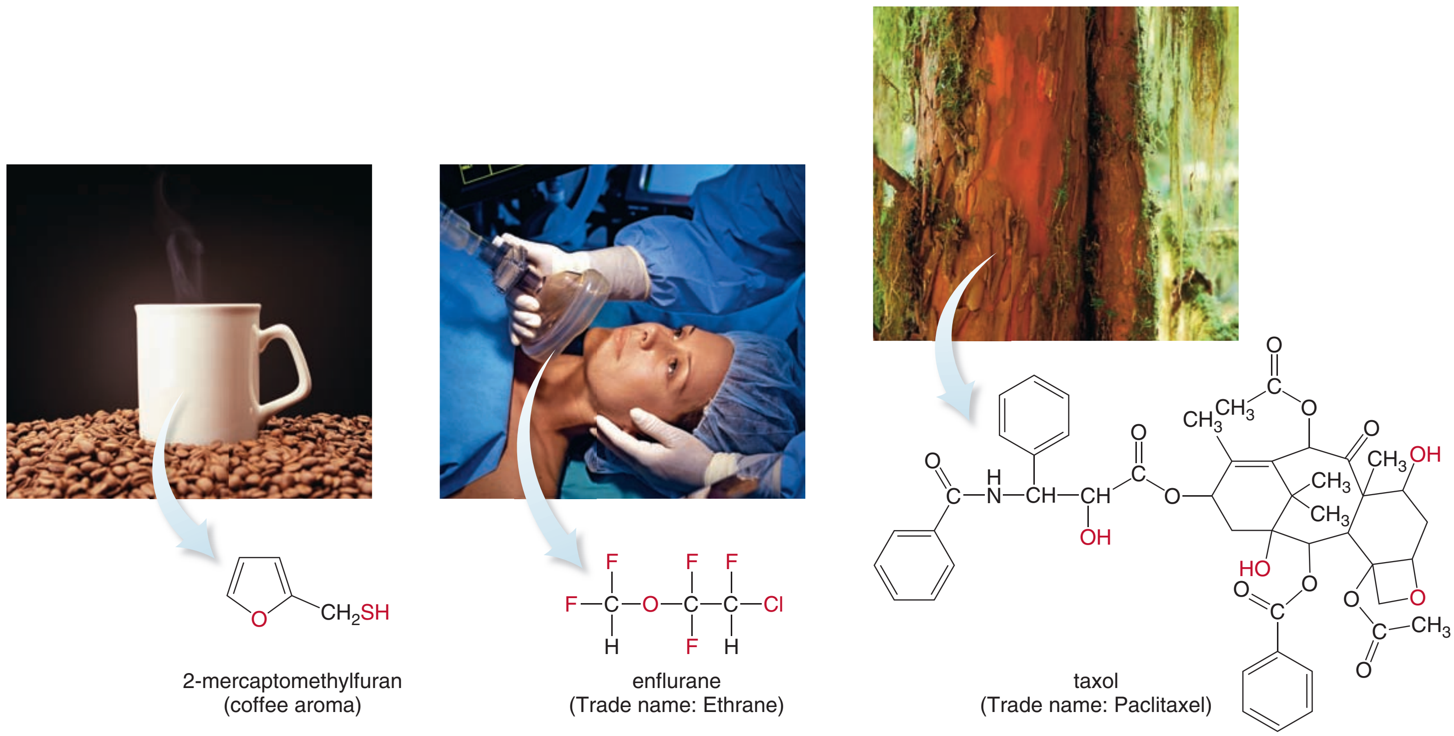
Alcohols and **ethers** are organic derivatives of H_2O, formed by replacing one or two hydrogens on the oxygen by alkyl groups, respectively. ***Alcohols* contain a hydroxyl group (OH group)** bonded to a tetrahedral carbon atom, while ***ethers* have two alkyl groups bonded to an oxygen atom.** The oxygen atom in both compounds has two lone pairs of electrons, so it is surrounded by eight electrons.



Alkyl halides contain a halogen atom (X = F, Cl, Br, or I) bonded to a tetrahedral carbon. Each halogen atom forms one bond to carbon and has three lone pairs of electrons. **Thiols contain a sulfhydryl group (SH group)** bonded to a tetrahedral carbon atom. A thiol is a sulfur analogue of an alcohol, formed by replacing the oxygen by sulfur. Like oxygen, the sulfur atom has two lone pairs of electrons around it.



Mercaptomethylfuran (characteristic aroma of coffee), enflurane (a common anesthetic), and taxol (an anticancer drug) are compounds that contain these functional groups.

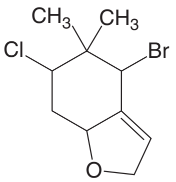


[The OH, SH, halogen, and ether O atoms are labeled in red.]

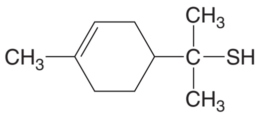
Taxol, a complex anticancer agent active against ovarian, breast, and some lung tumors, is especially interesting. Initial biological studies with taxol were carried out with natural material isolated from the bark of the Pacific yew tree, but stripping the bark killed these magnificent trees. Taxol is now synthesized in the laboratory in four steps from a compound isolated from the needles of the common English yew tree, thus providing ample quantities for patients.

PROBLEM 14.1

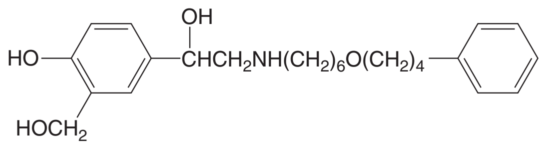
a. Label the –OH groups, –SH groups, halogens, and ether oxygens in each compound.
b. Which –OH group in salmeterol (**C**) is *not* part of an alcohol? Explain.



A
chondrochole A
(isolated from red seaweed, *Chondrococcus hornemanni*)



B
(responsible for the characteristic flavor of grapefruit)



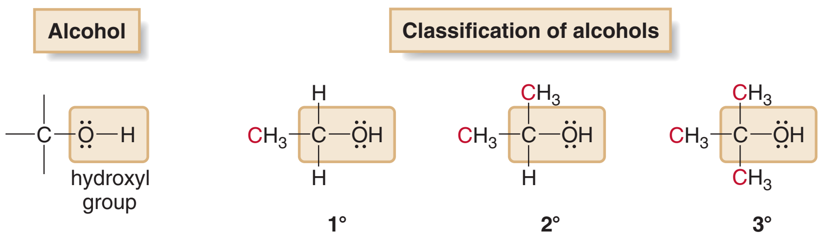
C
salmeterol
Trade name: Serevent
(dilates airways; used to treat asthma)

PROBLEM 14.2

Besides its three hydroxyl groups and one ether oxygen, taxol contains 10 other functional groups. Identify each of these functional groups.

14.2 STRUCTURE AND PROPERTIES OF ALCOHOLS

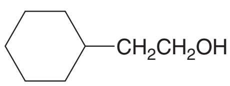
***Alcohols* contain a hydroxyl group** (**OH** group) bonded to a tetrahedral carbon atom. Alcohols are classified as **primary (1°), secondary (2°),** or **tertiary (3°)** based on the number of carbon atoms bonded to the carbon with the OH group.

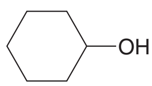


- **A primary (1°) alcohol has an OH group on a carbon bonded to one carbon.**
- **A secondary (2°) alcohol has an OH group on a carbon bonded to two carbons.**
- **A tertiary (3°) alcohol has an OH group on a carbon bonded to three carbons.**

SAMPLE PROBLEM 14.1

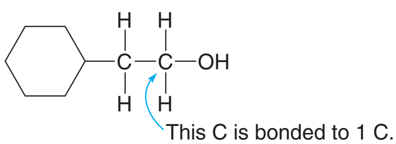
Classify each alcohol as 1°, 2°, or 3°.

a. 

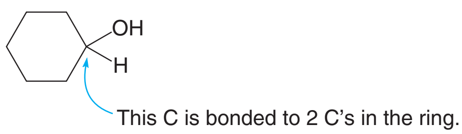
b. 

ANALYSIS To determine whether an alcohol is 1°, 2°, or 3°, locate the C with the OH group and count the number of C's bonded to it. A 1° alcohol has the OH group on a C bonded to one C, and so forth.

SOLUTION Draw out the structure or add H's to the skeletal structure to clearly see how many C's are bonded to the C bearing the OH group.

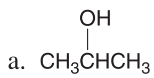
a. 

1° alcohol

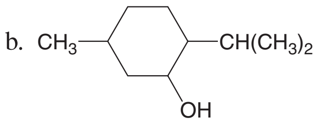
b. 

2° alcohol

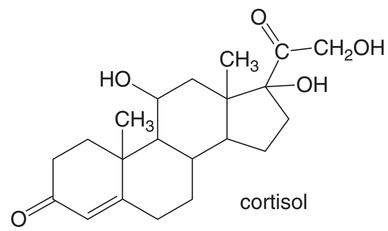
PROBLEM 14.3 Classify each alcohol as 1°, 2°, or 3°.

a. 

2-propanol

b. 

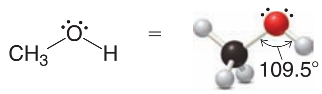
menthol

c. 

cortisol

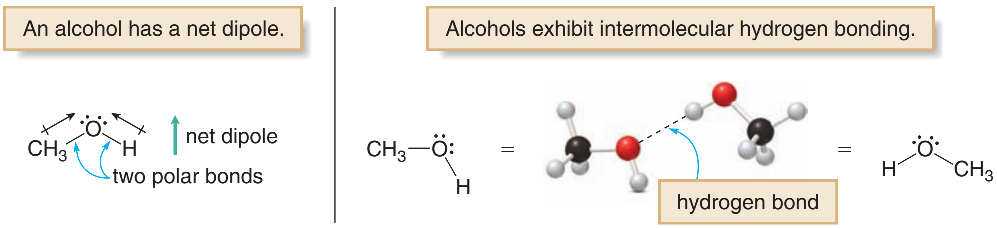
(an anti-inflammatory agent that also regulates carbohydrate metabolism)

An alcohol contains an oxygen atom surrounded by two atoms and two lone pairs of electrons, giving the oxygen atom a **bent** shape like H_2O. The C—O—H bond angle is similar to the tetrahedral bond angle of 109.5°.



methanol   bent shape

Because oxygen is much more electronegative than carbon or hydrogen, the C—O and O—H bonds are polar. Since an alcohol contains two polar bonds and a bent shape, it has a net dipole. **Alcohols are also capable of intermolecular hydrogen bonding,** since they possess a hydrogen atom bonded to an oxygen. This gives alcohols much stronger intermolecular forces than the hydrocarbons of Chapters 12 and 13.



As a result:

- **Alcohols have higher boiling points and melting points than hydrocarbons of comparable size and shape.**

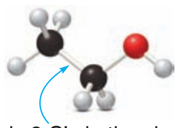
$CH_3CH_2CH_2CH_3$	$CH_3CH_2CH_2OH$ ← **stronger intermolecular forces higher boiling point and melting point**
butane	1-propanol
melting point: −138 °C boiling point: −0.5 °C	melting point: −127 °C boiling point: 97 °C

The general rule governing solubility—**"like dissolves like"**—explains the solubility properties of alcohols, as we learned in Section 11.6B.

- **Alcohols are soluble in organic solvents.**
- **Low molecular weight alcohols (those having less than six carbons) are soluble in water.**
- **Higher molecular weight alcohols (those having six carbons or more) are not soluble in water.**

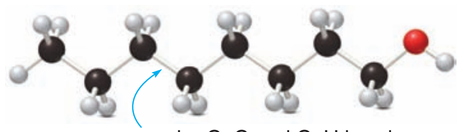
Thus, both ethanol (CH_3CH_2OH) and 1-octanol [$CH_3(CH_2)_7OH$] are soluble in organic solvents, but ethanol is water soluble and 1-octanol is not.

CH_3CH_2OH



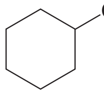
only 2 C's in the chain
water soluble

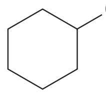
$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2OH$



many nonpolar C–C and C–H bonds
water insoluble

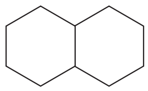
PROBLEM 14.4 Which compound in each pair has the higher boiling point?

a. 

or 

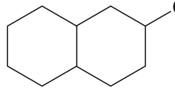
b. $(CH_3)_3C—OH$ or $(CH_3)_4C$

PROBLEM 14.5 Label each compound as water soluble or water insoluble.

a. 

b. $(CH_3)_3C—OH$

c. $CH_2{=}CHCH_2CH_3$

d. 

14.3 NOMENCLATURE OF ALCOHOLS

In the IUPAC system, alcohols are identified by the suffix ***-ol.***

HOW TO Name an Alcohol Using the IUPAC System

EXAMPLE **Give the IUPAC name of the following alcohol.**

CH_3 OH
$CH_3CHCH_2CHCH_2CH_3$

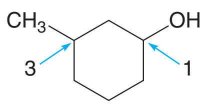
Step [1] **Find the longest carbon chain containing the carbon bonded to the OH group.**

CH_3 OH $CH_3CHCH_2CHCH_2CH_3$ **6** C's in the longest chain **hexane** ---→ **hexan*ol***	• Change the ***-e*** ending of the parent alkane to the suffix ***-ol.***

Step [2] **Number the carbon chain to give the OH group the lower number, and apply all other rules of nomenclature.**

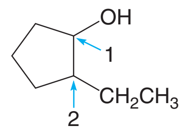
a. **Number** the chain. CH_3 OH $CH_3CHCH_2CHCH_2CH_3$ 6 5 4 3 2 1 • Number the chain to put the OH group at C3, not C4. 3-hexanol	b. **Name** and **number** the substituents. methyl at C5 CH_3 OH $CH_3CHCH_2CHCH_2CH_3$ 5 3 **Answer: 5-methyl-3-hexanol**

When an OH group is bonded to a ring, the **ring is numbered beginning with the OH group,** and the "1" is usually omitted from the name. The ring is then numbered in a clockwise or counterclockwise fashion to give the next substituent the lower number.



3-methylcyclohexanol

[The OH group is at C1; the second substituent (CH_3) gets the lower number.]



2-ethylcyclopentanol

[The OH group is at C1; the second substituent (CH_3CH_2) gets the lower number.]

Common names are often used for simple alcohols. To assign a common name:

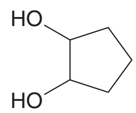
- **Name all the carbon atoms of the molecule as a single alkyl group.**
- **Add the word *alcohol,* separating the words with a space.**

$CH_3CH_2CH_2$—OH (propyl group) → alcohol ---→ **propyl alcohol** (a common name)

Compounds with two hydroxyl groups are called **diols** (using the IUPAC system) or **glycols.** Compounds with three hydroxyl groups are called **triols,** and so forth. To name a diol, for example, the suffix ***-diol*** is added to the name of the parent alkane and numbers are used in the prefix to indicate the location of the two OH groups.

$HOCH_2CH_2OH$

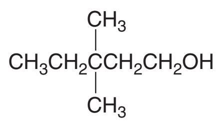
IUPAC name: 1,2-ethanediol
Common name: **ethylene glycol**



1,2-cyclopentanediol

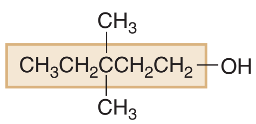
SAMPLE PROBLEM 14.2

Give the IUPAC name of the following alcohol.



ANALYSIS AND SOLUTION

[1] **Find the longest carbon chain that contains the carbon bonded to the OH group.**

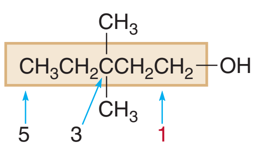


5 C's in the longest chain ---→ **pentanol**

- Change the ***-e*** ending of the parent alkane to the suffix ***-ol.***

[2] **Number the carbon chain to give the OH group the lower number, and apply all other rules of nomenclature.**

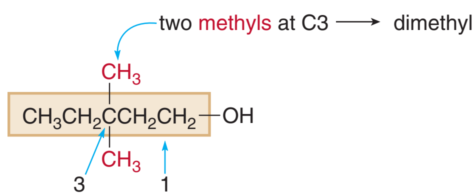
a. **Number** the chain.



- Number the chain to put the OH group at C1, not C5.

1-pentanol

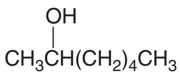
b. **Name** and **number** the substituents.

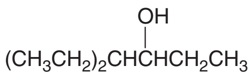


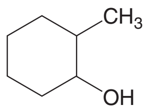
Answer: 3,3-dimethyl-1-pentanol

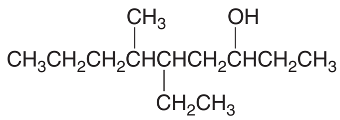
PROBLEM 14.6

Give the IUPAC name for each compound.

a. 

b. 

c. 

d. 

PROBLEM 14.7

Give the structure corresponding to each name.

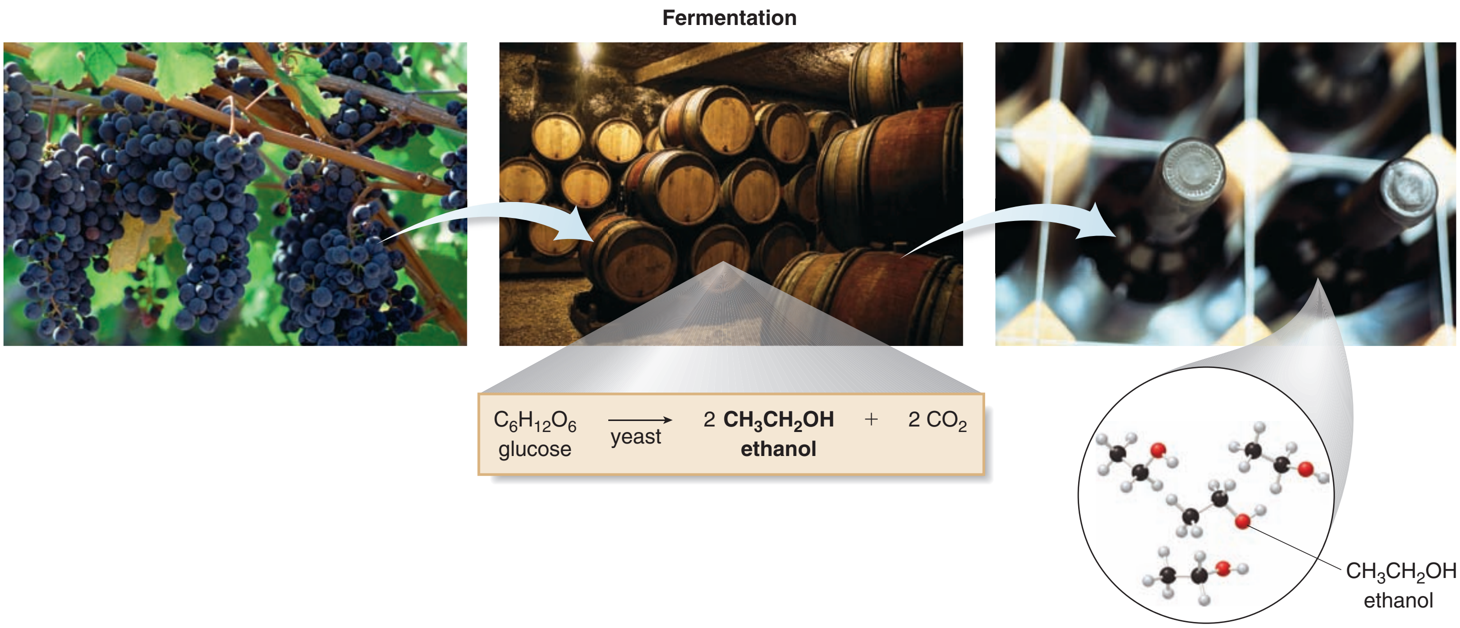
a. 7,7-dimethyl-4-octanol
b. 5-methyl-4-propyl-3-heptanol
c. 2-ethyl-3-methylcyclohexanol
d. 1,3-cyclohexanediol

14.4 INTERESTING ALCOHOLS

The most well known alcohol is ethanol, CH_3CH_2OH. **Ethanol** (Figure 14.1), formed by the fermentation of carbohydrates in grains and grapes, is the alcohol present in alcoholic beverages. Fermentation requires yeast, which provides the needed enzymes for the conversion. Ethanol is likely the first organic compound synthesized by humans, since alcohol has been produced for at least 4,000 years.

Ethanol is also a common laboratory solvent, which is sometimes made unfit to ingest by adding small amounts of benzene or methanol (CH_3OH), both of which are toxic. Ethanol is used as a gasoline additive since it readily combusts to form CO_2 and H_2O with the release of energy. Other simple alcohols are listed in Figure 14.2.

FIGURE 14.1 Ethanol—The Alcohol in Alcoholic Beverages



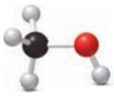
Ethanol is the alcohol in red wine, obtained by the fermentation of grapes. All alcoholic beverages are mixtures of ethanol and water in various proportions. Beer has 3–8% ethanol, wines have 10–14% ethanol, and other liquors have 35–90% ethanol.

CONSUMER NOTE



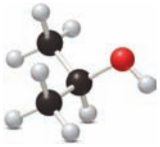
Gasohol (also called E–10 Unleaded) contains 10% ethanol.

FIGURE 14.2 Some Simple Alcohols



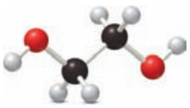
CH_3OH

- **Methanol (CH_3OH)** is a useful solvent and starting material for the synthesis of plastics. Methanol is extremely toxic because of the oxidation products formed when metabolized in the liver (Section 14.6A). Ingestion of as little as 15 mL (about half an ounce) causes blindness and 100 mL causes death.



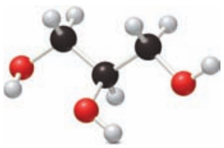
$(CH_3)_2CHOH$

- **2-Propanol [$(CH_3)_2CHOH$, isopropyl alcohol]** is the major component of rubbing alcohol. When rubbed on the skin it evaporates readily, producing a pleasant cooling sensation. 2-Propanol is used to clean skin before medical procedures and to sterilize medical instruments.



$HOCH_2CH_2OH$

- **Ethylene glycol ($HOCH_2CH_2OH$)** is the major component of antifreeze. It is sweet tasting but extremely toxic. Ethylene glycol is a starting material in the synthesis of synthetic fibers such as Dacron (Section 17.10).

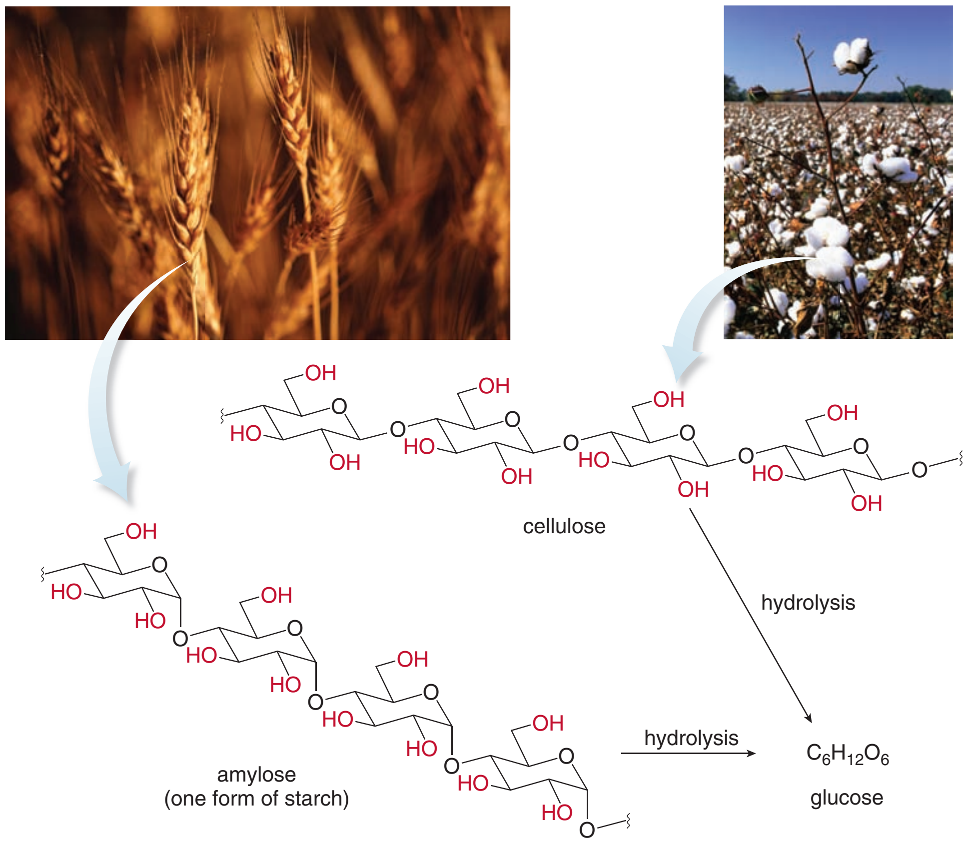


$HOCH_2CH(OH)CH_2OH$

- **Glycerol [$(HOCH_2)_2CHOH$]** is a triol used in lotions, liquid soap, and shaving cream. Since it is sweet tasting and nontoxic, it is also an additive in candy and some prepared foods. Its three OH groups readily hydrogen bond to water, so it helps to retain moisture in these products.

The six-membered rings in starch and cellulose are drawn in the puckered “chair” form mentioned in Section 12.5A.

Starch and **cellulose** are two polymers that contain many OH groups and belong to the family of molecules called **carbohydrates.**



Starch is the main carbohydrate in the seeds and roots of plants. When humans ingest wheat, rice, and potatoes, for example, they consume starch, which is then hydrolyzed to the simple sugar **glucose. Cellulose,** nature's most abundant organic material, gives rigidity to tree trunks and plant stems. Wood, cotton, and flax are composed largely of cellulose. Complete hydrolysis of cellulose also forms glucose, but unlike starch, humans cannot metabolize cellulose to glucose; that is, humans can digest starch but not cellulose.

PROBLEM 14.8 Write a balanced equation for the combustion of ethanol with O_2 to form CO_2 and H_2O.

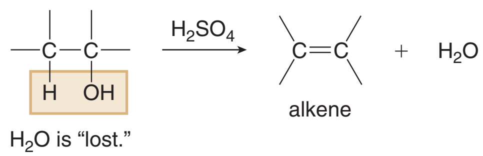
14.5 REACTIONS OF ALCOHOLS

Alcohols undergo two useful reactions—**dehydration** and **oxidation.**

14.5A DEHYDRATION

When an alcohol is treated with a strong acid such as H_2SO_4, the elements of water are lost and an alkene is formed as product. **Loss of H_2O from a starting material is called *dehydration*.** Dehydration takes place by breaking bonds on two adjacent atoms—the C—OH bond and an adjacent C—H bond.

Dehydration

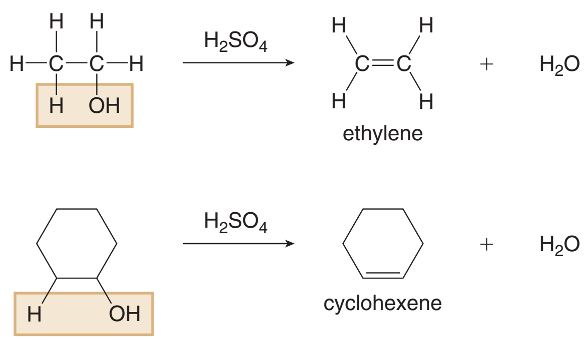


Dehydration is an example of a general type of organic reaction called an **elimination reaction.**

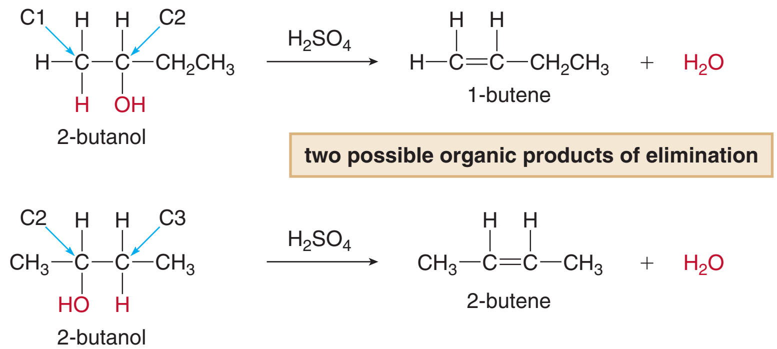
- ***Elimination*** **is a reaction in which elements of the starting material are "lost" and a new multiple bond is formed.**

For example, dehydration of ethanol (CH_3CH_2OH) with H_2SO_4 forms ethylene ($CH_2{=}CH_2$), as shown. To draw the product of any dehydration, remove the elements of H and OH from two adjacent atoms and draw a carbon–carbon double bond in the product.

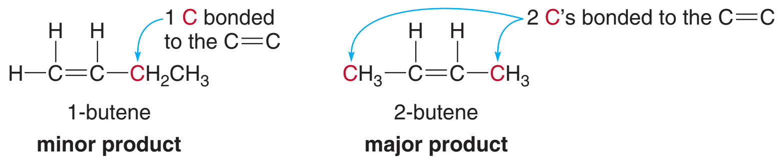
Examples



Sometimes more than one alkene can be formed as the product of a dehydration reaction, as is the case when 2-butanol [$CH_3CH(OH)CH_2CH_3$] is the starting material. If H and OH are removed from C1 and C2, 1-butene is formed. If H and OH are removed from C3 and C2, 2-butene is formed.



Although both products are formed, **the major product is the alkene with more alkyl groups bonded to the carbons of the double bond.** In this case, therefore, 2-butene is the major product, because its C═C has two alkyl groups (two CH_3 groups) bonded to it, whereas the C═C of 1-butene has only one alkyl group (one CH_2CH_3 group) bonded to it.

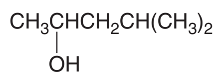


This is a specific example of a general trend called the **Zaitsev rule.**

- **The Zaitsev rule: The major product in elimination is the alkene that has more alkyl groups bonded to it.**

SAMPLE PROBLEM 14.3

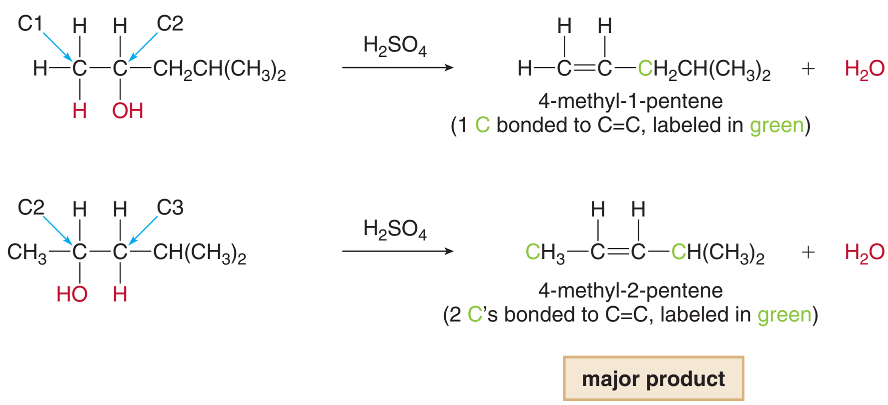
Draw all possible products of dehydration of the following alcohol, and predict which one is the major product.



ANALYSIS To draw the products of dehydration:

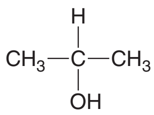
- First find the carbon bonded to the OH group, and then identify all carbons with H's bonded to this carbon.
- Remove the elements of H and OH from two adjacent C's, and draw a double bond between these C's in the product.
- When two different alkenes are formed, the major product has more C's bonded to the C═C.

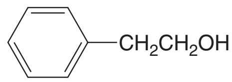
SOLUTION In this example, there are two different C's bonded to the C with the OH. Elimination of H and OH from C1 and C2 forms 4-methyl-1-pentene. Elimination of H and OH from C3 and C2 forms 4-methyl-2-pentene. The major product is 4-methyl-2-pentene because it has two C's bonded to the C═C, whereas 4-methyl-1-pentene has only one C bonded to the C═C.

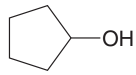


PROBLEM 14.9

Draw the products formed when each alcohol is dehydrated with H_2SO_4.

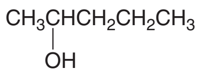
a. 

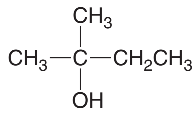
b. 

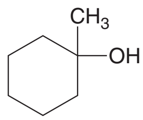
c. 

PROBLEM 14.10

What alkenes are formed when each alcohol is treated with H_2SO_4? Use the Zaitsev rule to predict the major product.

a. 

b. 

c. 

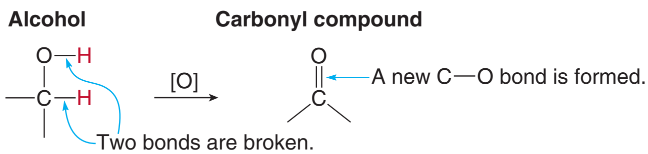
14.5B OXIDATION

Recall from Section 12.8 that to determine if an organic compound has been oxidized, we compare the relative number of C—H and C—O bonds in the starting material and product.

- **Oxidation results in an increase in the number of C—O bonds or a decrease in the number of C—H bonds.**

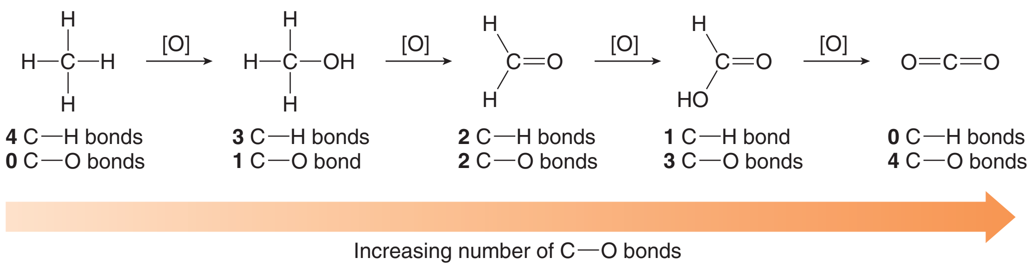
Thus, an organic compound like CH_4 can be oxidized by replacing C—H bonds with C—O bonds, as shown in Figure 14.3. When an alkane like CH_4 undergoes complete oxidation, as it does during combustion, all C—H bonds are converted to C—O bonds, forming CO_2. Organic chemists use the symbol [O] to indicate oxidation.

Alcohols can be oxidized to a variety of compounds, depending on the type of alcohol and the reagent. **Oxidation occurs by replacing the C—H bonds *on the carbon bearing the OH group* by C—O bonds.** All oxidation products from alcohol starting materials contain a **C=O, a carbonyl group.**

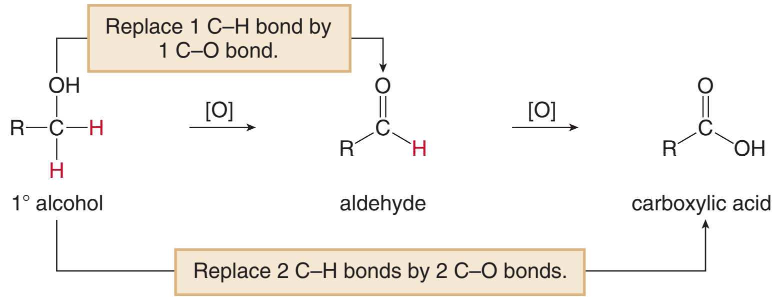


A common reagent for alcohol oxidation is potassium dichromate, $\mathbf{K_2Cr_2O_7}$, a red-orange solid. During oxidation the reagent is converted a green Cr^{3+} product. Thus, these oxidations are accompanied by a characteristic color change. Since a variety of reagents can be used, we will write oxidation with the general symbol for oxidation, [O].

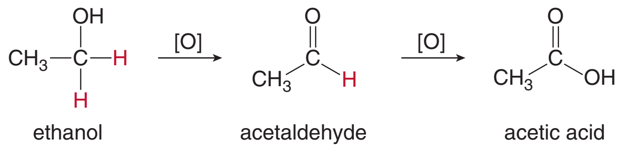
FIGURE 14.3 A General Scheme for Oxidizing an Organic Compound



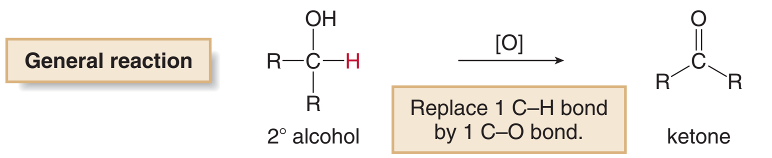
- **Primary (1°) alcohols are first oxidized to aldehydes (RCHO), which are further oxidized to carboxylic acids (RCOOH) by replacing one and then two C—H bonds by C—O bonds.**

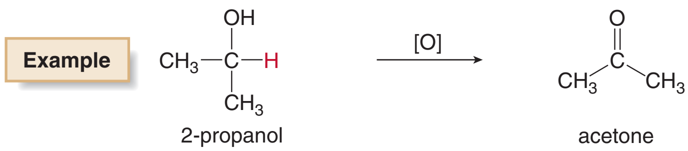


Thus, oxidation of one C—H bond of ethanol forms acetaldehyde. Since acetaldehyde still contains a hydrogen atom on the carbonyl carbon, converting this C—H bond to a C—O bond forms acetic acid, a carboxylic acid with three C—O bonds.



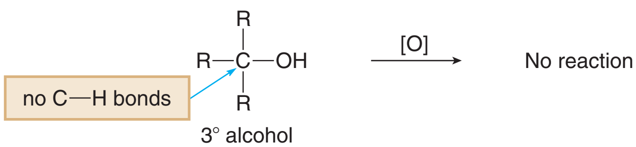
- **Secondary (2°) alcohols are oxidized to ketones (R_2CO), by replacing one C—H bond by one C—O bond.**





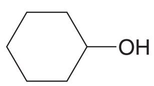
Since 2° alcohols have only one hydrogen atom bonded to the carbon with the OH group, they can be oxidized to only one type of compound, a ketone. Thus, 2-propanol is oxidized to acetone.

- **Tertiary 3° alcohols have no H atoms on the carbon with the OH group, so they are not oxidized.**



SAMPLE PROBLEM 14.4

Draw the carbonyl products formed when each alcohol is oxidized with $K_2Cr_2O_7$.

a. 

cyclohexanol

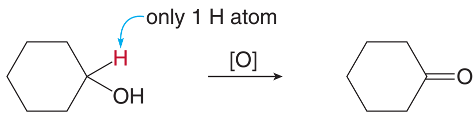
b. $CH_3CH_2CH_2CH_2OH$

1-butanol

ANALYSIS Classify the alcohol as 1°, 2°, or 3° by drawing in all of the H atoms on the C with the OH. Then concentrate on the C with the OH group and replace H atoms by bonds to O. Keep in mind:

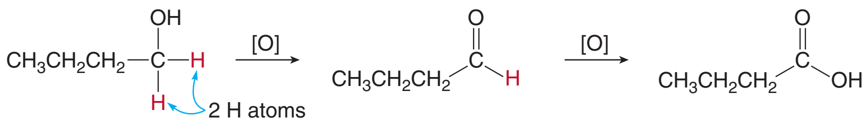
- RCH_2OH (1° alcohols) are oxidized to RCHO, which are then oxidized to RCOOH.
- R_2CHOH (2° alcohols) are oxidized to R_2CO.
- R_3COH (3° alcohols) are not oxidized since they have no H atom on the C with the OH.

SOLUTION a. Since cyclohexanol is a 2° alcohol with only one H atom on the C bonded to the OH group, it is oxidized to a ketone, cyclohexanone.



cyclohexanol — 2° alcohol; cyclohexanone — ketone

b. 1-Butanol is a 1° alcohol with two H atoms on the C bonded to the OH group. Thus, it is first oxidized to an aldehyde and then to a carboxylic acid.

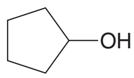


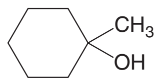
1-butanol — 1° alcohol; butanal — aldehyde; butanoic acid — carboxylic acid

PROBLEM 14.11 What products are formed when each alcohol is oxidized with $K_2Cr_2O_7$? In some cases, no reaction occurs.

a. $CH_3CHCH_2CH_2CH_3$ (with OH on the second carbon)

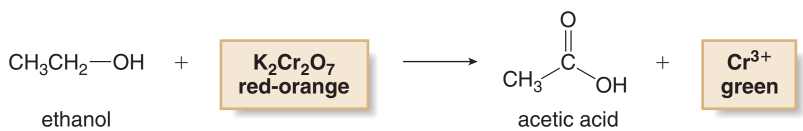
b. $(CH_3)_3CCH_2CH_2OH$

c. 

d. 

14.5C FOCUS ON THE HUMAN BODY OXIDATION AND BLOOD ALCOHOL SCREENING

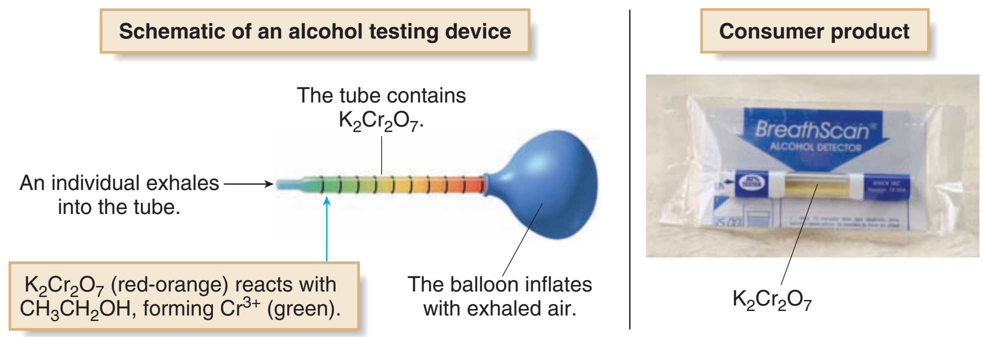
Oxidations with chromium reagents are characterized by a color change, as the **red-orange chromium reagent** is reduced to a **green Cr^{3+} product.** The first devices used to measure blood alcohol content in individuals suspected of "driving under the influence," made use of this color change. Oxidation of CH_3CH_2OH, the 1° alcohol in alcoholic beverages, with red-orange $K_2Cr_2O_7$ forms CH_3COOH and green Cr^{3+}.



ethanol "alcohol"; acetic acid

Blood alcohol level can be determined by having an individual blow into a tube containing $K_2Cr_2O_7$ and an inert solid. The alcohol in the exhaled breath is oxidized by the chromium reagent, which turns green in the tube (Figure 14.4). The higher the concentration of CH_3CH_2OH in the breath, the more chromium reagent is reduced, and the farther the green color extends down the length of the sample tube. This value is then correlated with blood alcohol content to determine if an individual has surpassed the legal blood alcohol limit.

FIGURE 14.4 Blood Alcohol Screening



- The oxidation of CH_3CH_2OH with $K_2Cr_2O_7$ to form CH_3COOH and Cr^{3+} was the first available method for the routine testing of alcohol concentration in exhaled air. Some consumer products for alcohol screening are still based on this technology.
- A driver is considered "under the influence" in most states with a blood alcohol concentration of 0.08%.

14.6 FOCUS ON HEALTH & MEDICINE ETHANOL, THE MOST WIDELY ABUSED DRUG



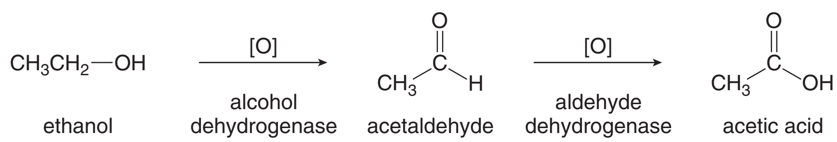
While alcohol use is socially acceptable, alcohol-related traffic fatalities are common with irresponsible alcohol consumption. In 2004, almost 40% of all fatalities in car crashes in the United States were alcohol-related.

Throughout history, humans have ingested alcoholic beverages for their pleasant taste and the feeling of euphoria they impart. Although we think of alcohol as a stimulant, largely because small amounts decrease social inhibitions, the ethanol (CH_3CH_2OH) in an alcoholic beverage actually depresses the central nervous system. The chronic and excessive consumption of alcoholic beverages has become a major health and social crisis, making ethanol the most widely abused drug in the United States. One estimate suggests that there are 40 times more alcoholics than heroin addicts.

14.6A THE METABOLISM OF ETHANOL

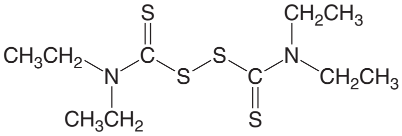
When ethanol is consumed, it is quickly absorbed in the stomach and small intestines and then rapidly transported in the bloodstream to other organs. Ethanol is metabolized in the liver, by a two-step oxidation sequence. The body does not use chromium reagents as oxidants. Instead, high molecular weight enzymes, alcohol dehydrogenase and aldehyde dehydrogenase, and a small molecule called a **coenzyme** carry out these oxidations.

The products of the biological oxidation of ethanol are the same as the products formed in the laboratory. When ethanol (CH_3CH_2OH, a 1° alcohol) is ingested, it is oxidized in the liver first to CH_3CHO (acetaldehyde), and then to CH_3COOH (acetic acid).



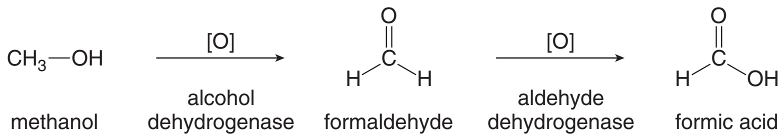
If more ethanol is ingested than can be metabolized in a given time period, the concentration of acetaldehyde accumulates. This toxic compound is responsible for the feelings associated with a hangover.

Antabuse, a drug given to alcoholics to prevent them from consuming alcoholic beverages, acts by interfering with the normal oxidation of ethanol. Antabuse inhibits the oxidation of acetaldehyde to acetic acid. Since the first step in ethanol metabolism occurs but the second does not, the concentration of acetaldehyde rises, causing an individual to become violently ill.



Antabuse

Methanol (CH_3OH, Section 14.4) is toxic because of these same oxidation reactions. Methanol is oxidized by enzymes to yield formaldehyde and formic acid. Both of these oxidation products are extremely toxic since they cannot be further metabolized by the body. As a result, the pH of the blood decreases, and blindness and death can follow.



Since the enzymes have a higher affinity for ethanol than methanol, methanol poisoning is treated by giving ethanol to an individual. With both methanol and ethanol in a patient's system, the enzymes react more readily with ethanol, allowing the methanol to be excreted unchanged without the formation of methanol's toxic oxidation products.

PROBLEM 14.12 Ethylene glycol, $HOCH_2CH_2OH$, is an extremely toxic diol because its oxidation products are also toxic. Draw the oxidation products formed during the metabolism of ethylene glycol.

14.6B HEALTH EFFECTS OF ALCOHOL CONSUMPTION

Alcohol consumption has both short-term and long-term effects. In small amounts it can cause dizziness, giddiness, and a decrease in social inhibitions. In larger amounts it decreases coordination and reaction time and causes drowsiness. Intoxicated individuals have exaggerated emotions, slurred speech, amnesia, and a lack of coordination. Coma and death can result at even higher concentrations.

Ethanol affects many organs. It dilates blood vessels, resulting in a flushed appearance. It increases urine production and stimulates the secretion of stomach acid. Chronic excessive alcohol consumption damages the heart and can lead to **cirrhosis of the liver,** an incurable and fatal disorder in which the liver is scarred and loses its ability to function.

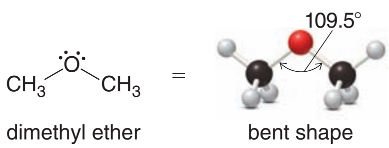
The consumption of ethanol during pregnancy is not recommended. The liver of a fetus does not contain the necessary enzyme to metabolize ethanol. As a result, any alcohol consumed by a pregnant woman crosses the placenta and can cause a variety of abnormalities. **Fetal alcohol syndrome** can result in infants of women who chronically consume alcohol during pregnancy. Infants with fetal alcohol syndrome are mentally retarded, grow poorly, and have certain facial abnormalities. Even modest alcohol consumption during pregnancy can negatively affect the fetus. Currently the American Medical Association recommends that a woman completely abstain from alcohol during pregnancy.

14.7 STRUCTURE AND PROPERTIES OF ETHERS

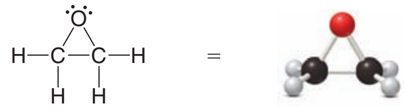
***Ethers* are organic compounds that have two alkyl groups bonded to an oxygen atom.** These two alkyl groups can be the same, or they can be different.

$R—\ddot{O}—R$	$CH_3CH_2—\ddot{O}—CH_2CH_3$	$CH_3—\ddot{O}—CH_2CH_3$
ether	R groups are the **same.**	R groups are **different.**

The oxygen atom of an ether is surrounded by two carbon atoms and two lone pairs of electrons, giving it a **bent** shape like the oxygen in H_2O. The C—O—C bond angle is similar to the tetrahedral bond angle of 109.5°.



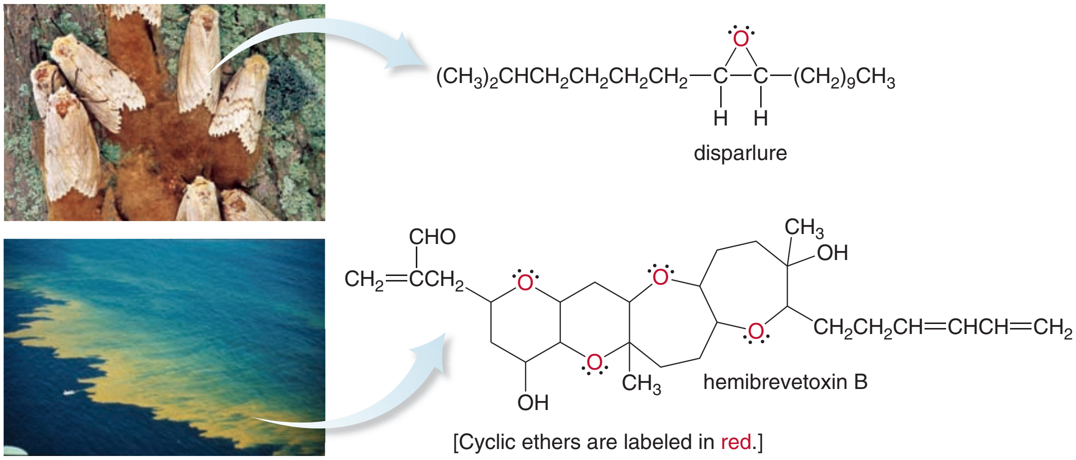
The ether oxygen can be contained in a ring. **A ring that contains a heteroatom is called a heterocycle.** When the ether is part of a three-membered ring, the ether is called an ***epoxide.***



HEALTH NOTE

Shellfish collected during red tides may contain high levels of neurotoxins, making it unfit for human consumption.

Many compounds that contain ether heterocycles are naturally occurring. **Disparlure,** the sex pheromone of the female gypsy moth, is an epoxide used to control the spread of the gypsy moth caterpillar. This pest has periodically devastated the forests of the northeastern United States by eating the leaves of many shade and fruit-bearing trees. **Hemibrevetoxin B,** a complex neurotoxin with four ether oxygens, is produced by algal blooms referred to as "red tides," because of the color of the ocean waters when these algae proliferate.



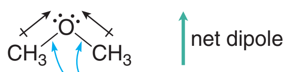
[Cyclic ethers are labeled in red.]

PROBLEM 14.13 What other functional groups are present in hemibrevetoxin B?

PROBLEM 14.14 Draw the structure of the three constitutional isomers of molecular formula $C_4H_{10}O$ that contain an ether.

14.7A PHYSICAL PROPERTIES

Because oxygen is more electronegative than carbon, the C—O bonds of an ether are both polar. Since an ether contains two polar bonds and a bent shape, it has a **net dipole.** In this way, ethers resemble alcohols.



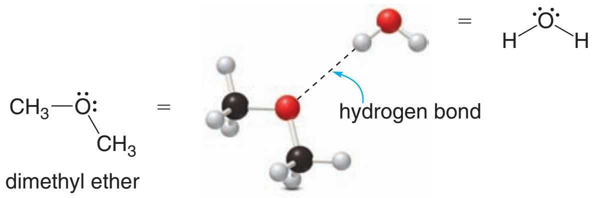
Ethers do not contain a hydrogen atom bonded to oxygen, so unlike alcohols, two ether molecules *cannot* intermolecularly hydrogen bond to each other. **This gives ethers stronger intermolecular forces than alkanes but weaker intermolecular forces than alcohols.** As a result:

- **Ethers have higher melting points and boiling points than hydrocarbons of comparable size and shape.**
- **Ethers have lower melting points and boiling points than alcohols of comparable size and shape.**

$CH_3CH_2CH_2CH_3$	$CH_3OCH_2CH_3$	$CH_3CH_2CH_2OH$
butane	ethyl methyl ether	1-propanol
boiling point −0.5 °C	boiling point 11 °C	boiling point 97 °C

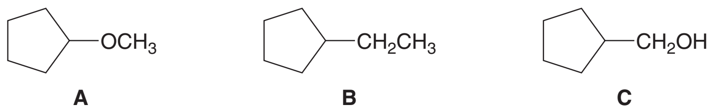
Increasing boiling point →

All ethers are soluble in organic solvents. Like alcohols, **low molecular weight ethers are water soluble,** because the oxygen atom of the ether can hydrogen bond to one of the hydrogens of water. When the alkyl groups of the ether have more than a total of five carbons, the nonpolar portion of the molecule is too large, so the ether is water insoluble.



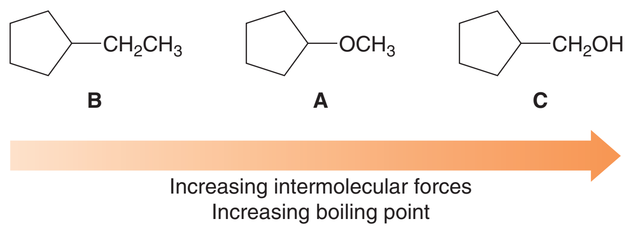
SAMPLE PROBLEM 14.5

Rank the following compounds in order of increasing boiling point:



ANALYSIS Look at the functional groups to determine the strength of the intermolecular forces—**the stronger the forces, the higher the boiling point.**

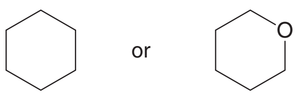
SOLUTION **B** is an alkane with nonpolar C—C and C—H bonds, so it has the weakest intermolecular forces and therefore the lowest boiling point. **C** is an alcohol capable of intermolecular hydrogen bonding, so it has the strongest intermolecular forces and the highest boiling point. **A** is an ether, so it contains a net dipole but is incapable of intermolecular hydrogen bonding. **A,** therefore, has intermolecular forces of intermediate strength and has a boiling point between the boiling points of **B** and **C.**



PROBLEM 14.15

Which compound in each pair has the higher boiling point?

a. $CH_3(CH_2)_6CH_3$ or $CH_3(CH_2)_5OCH_3$

b. 

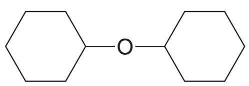
c. $CH_3(CH_2)_6OH$ or $CH_3(CH_2)_5OCH_3$

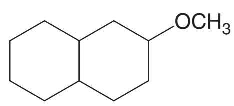
d. $CH_3(CH_2)_5OCH_3$ or CH_3OCH_3

PROBLEM 14.16

Label each ether as water soluble or water insoluble.

a. $CH_3CH_2—O—CH_3$

b. 

c. 

14.7B NAMING ETHERS

Simple ethers are usually assigned common names. To do so, **name both alkyl groups** bonded to the oxygen, arrange these names alphabetically, and add the word **ether.** For ethers with identical alkyl groups, name the alkyl group and add the prefix **di-.**

CH_3—O—CH_2CH_3	CH_3CH_2—O—CH_2CH_3
methyl, ethyl	ethyl, ethyl
ethyl methyl ether	**diethyl ether**

More complex ethers are named using the IUPAC system. One alkyl group is named as a hydrocarbon chain, and the other is named as part of a substituent bonded to that chain.

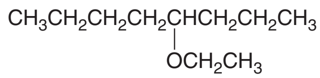
- **Name the simpler alkyl group + O atom as an alkoxy substituent by changing the *-yl* ending of the alkyl group to *-oxy.***

CH_3O–	CH_3CH_2O–
methoxy	ethoxy

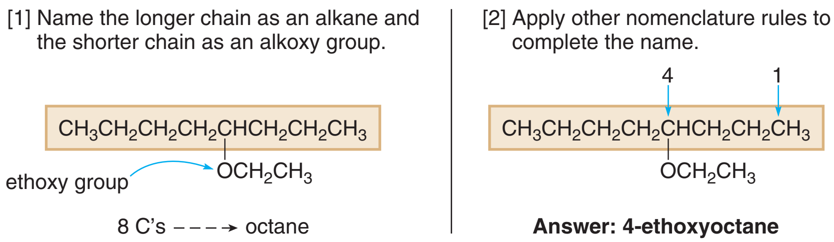
- **Name the remaining alkyl group as an alkane, with the alkoxy group as a substituent bonded to this chain.**

SAMPLE PROBLEM 14.6

Give the IUPAC name for the following ether.



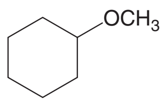
ANALYSIS AND SOLUTION



PROBLEM 14.17

Name each ether.

a. CH_3—O—$CH_2CH_2CH_2CH_3$

b. 

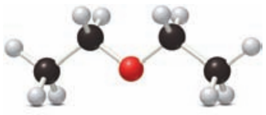
c. $CH_3CH_2CH_2$—O—$CH_2CH_2CH_3$

PROBLEM 14.18

Draw the structure corresponding to each name.

a. dibutyl ether
b. ethyl propyl ether
c. 1-methoxypentane
d. 3-ethoxyhexane

14.8 FOCUS ON HEALTH & MEDICINE ETHERS AS ANESTHETICS



diethyl ether

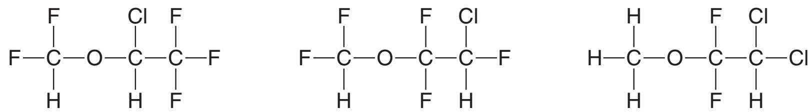
A general anesthetic is a drug that interferes with nerve transmission in the brain, resulting in a loss of consciousness and the sensation of pain. The discovery that **diethyl ether** ($CH_3CH_2OCH_2CH_3$) is a general anesthetic revolutionized surgery in the nineteenth century. Early experiments performed by a dentist, Dr. William Morton, resulted in a public demonstration of diethyl ether as an anesthetic in Boston in 1846. Diethyl ether quickly supplanted the crude methods then used for a patient to tolerate the excruciating pain of surgery—making an individual unconscious by excess alcohol intake or by striking a blow to the head.



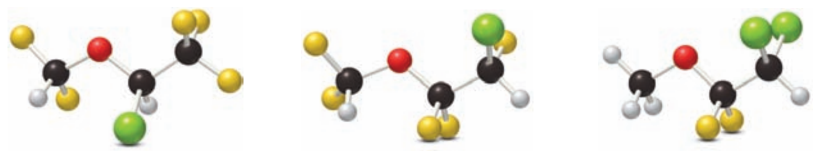
This painting by Robert Hinckley depicts a public demonstration of the use of diethyl ether as an anesthetic at the Massachusetts General Hospital in Boston, MA in the 1840s.

Diethyl ether is an imperfect anesthetic, but considering the alternatives in the nineteenth century, it was considered revolutionary. It is safe and easy to administer with low patient mortality, but it is highly flammable, and it causes nausea in many patients.

For these reasons, alternatives to diethyl ether are now widely used. Many of these newer general anesthetics, which cause little patient discomfort, are also ethers. These include isoflurane, enflurane, and methoxyflurane. Replacing some of the hydrogen atoms in the ether by halogens results in compounds with similar anesthetic properties but decreased flammability.



isoflurane (Trade name: Forane) | enflurane (Trade name: Ēthrane) | methoxyflurane (Trade name: Penthrane)



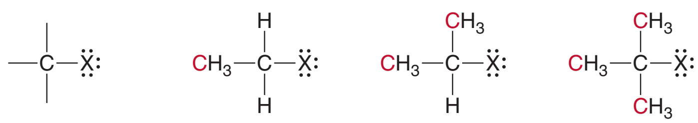
PROBLEM 14.19 Halothane ($CF_3CHClBr$) is a general anesthetic that is not an ether. Draw a three-dimensional structure for halothane using solid lines, wedges, and dashes (see Section 11.3).

14.9 ALKYL HALIDES

Alkyl halides have the general molecular formula $C_nH_{2n+1}X$, and are formally derived from an alkane by replacing a hydrogen atom with a halogen.

***Alkyl halides* are organic molecules containing a halogen atom X (X = F, Cl, Br, I) bonded to a tetrahedral carbon atom.** Alkyl halides are classified as **primary (1°), secondary (2°),** or **tertiary (3°)** depending on the number of carbons bonded to the carbon with the halogen.

Alkyl halide | **Classification of alkyl halides**

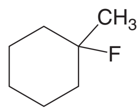


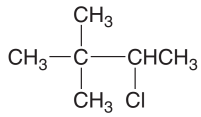
X = F, Cl, Br, I | **1°** | **2°** | **3°**

- A primary (1°) alkyl halide has a halogen on a carbon bonded to one carbon.
- A secondary (2°) alkyl halide has a halogen on a carbon bonded to two carbons.
- A tertiary (3°) alkyl halide has a halogen on a carbon bonded to three carbons.

PROBLEM 14.20 Classify each alkyl halide as 1°, 2°, or 3°.

a. $CH_3CH_2CH_2CH_2CH_2$—Br

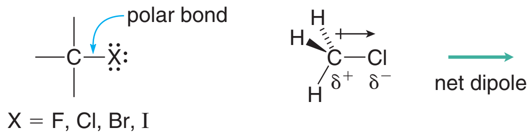
b. 

c. 

PROBLEM 14.21 Draw the structure of an alkyl halide that fits each description: (a) a 2° alkyl bromide of molecular formula C_4H_9Br; (b) a 3° alkyl chloride of molecular formula C_4H_9Cl; (c) a 1° alkyl fluoride of molecular formula C_3H_7F.

14.9A PHYSICAL PROPERTIES

Alkyl halides contain a polar C—X bond, but since they have all of their hydrogens bonded to carbon, they are incapable of intermolecular hydrogen bonding. Alkyl halides with one halogen are polar molecules, therefore, because they contain a net dipole. As a result, they have higher melting points and boiling points than alkanes with the same number of carbons.



The size of the alkyl groups and the halogen also affects the physical properties of an alkyl halide.

- **The boiling point and melting point of an alkyl halide increase with the size of the alkyl group because of increased surface area.**
- **The boiling point and melting point of an alkyl halide increase with the size of the halogen.**

Thus, $CH_3CH_2CH_2Cl$ has a higher boiling point than CH_3CH_2Cl because it has one more carbon, giving it a larger surface area. $CH_3CH_2CH_2Br$ has a higher boiling point than $CH_3CH_2CH_2Cl$ because Br is further down the column of the periodic table, making it larger than Cl.

CH_3CH_2Cl	$CH_3CH_2CH_2Cl$	$CH_3CH_2CH_2Br$
chloroethane	1-chloropropane	1-bromopropane
bp = 12 °C	bp = 47 °C	bp = 71 °C



Increasing boiling point
Increasing size of the alkyl group
Increasing size of the halogen

Since alkyl halides are incapable of hydrogen bonding, they are insoluble in water regardless of size.

PROBLEM 14.22 Rank the compounds in each group in order of increasing boiling point.

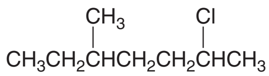
a. $CH_3CH_2CH_2I$, $CH_3CH_2CH_2Cl$, $CH_3CH_2CH_2F$
b. $CH_3(CH_2)_4CH_3$, $CH_3(CH_2)_5Br$, $CH_3(CH_2)_5Cl$

14.9B NOMENCLATURE

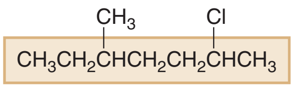
In the IUPAC system, an alkyl halide is named as an alkane with a halogen substituent—that is, as a ***halo alkane.*** To name a halogen substituent, change the ***-ine*** ending of the name of the halogen to the suffix ***-o*** (e.g., chlor*ine* → chlor*o*).

HOW TO Name an Alkyl Halide Using the IUPAC System

EXAMPLE **Give the IUPAC name of the following alkyl halide.**



Step [1] **Find the parent carbon chain containing the halogen.**



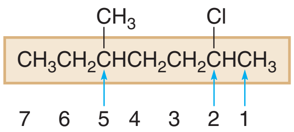
7 C's in the longest chain

7 C's ----→ **heptane**

- Name the parent chain as an ***alkane,*** with the halogen as a substituent bonded to the longest chain.

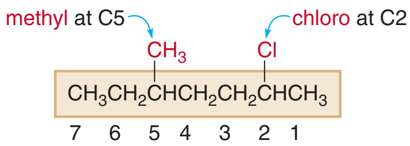
Step [2] **Apply all other rules of nomenclature.**

a. **Number** the chain.



- Begin at the end nearest the first substituent, either alkyl or halogen.

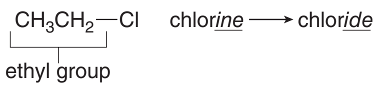
b. **Name** and **number** the substituents.



c. Alphabetize: *c* for **c**hloro, then *m* for **m**ethyl.

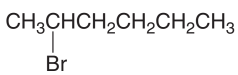
ANSWER: 2-chloro-5-methylheptane

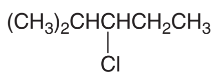
Common names for alkyl halides are used only for simple alkyl halides. To assign a common name, name the carbon atoms as an alkyl group. Then name the halogen by changing the ***-ine*** ending of the halogen name to the suffix ***-ide;*** for example, **brom*ine*** → **brom*ide*.**

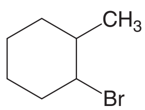


Common name: **ethyl chloride**

PROBLEM 14.23 Give the IUPAC name for each compound.

a. 

b. 

c. 

PROBLEM 14.24 Give the structure corresponding to each name.

a. 3-chloro-2-methylhexane

b. 4-ethyl-5-iodo-2,2-dimethyloctane

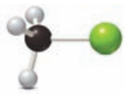
c. 1,1,3-tribromocyclohexane

d. propyl chloride

14.9C INTERESTING ALKYL HALIDES

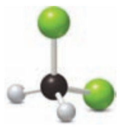
Many simple alkyl halides make excellent solvents because they are not flammable and they dissolve a wide variety of organic compounds. Two compounds in this category include $CHCl_3$ (chloroform or trichloromethane) and CCl_4 (carbon tetrachloride or tetrachloromethane). Large quantities of these solvents are produced industrially each year, but like many chlorinated organic compounds, both chloroform and carbon tetrachloride are toxic if inhaled or ingested. Two other simple alkyl halides are given in Figure 14.5.

FIGURE 14.5 Two Simple Alkyl Halides



CH_3Cl

- **Chloromethane (CH_3Cl)** is produced by giant kelp and algae and is also found in emissions from volcanoes such as Hawaii's Kilauea. Almost all of the atmospheric chloromethane results from these natural sources.



CH_2Cl_2

- **Dichloromethane (or methylene chloride, CH_2Cl_2)** is an important solvent, once used to decaffeinate coffee. Coffee is now decaffeinated using liquid CO_2 due to concerns over the possible ill effects of trace amounts of residual CH_2Cl_2 in the coffee. Subsequent studies on rats have shown, however, that no cancers occurred when animals ingested the equivalent of over 100,000 cups of decaffeinated coffee per day.

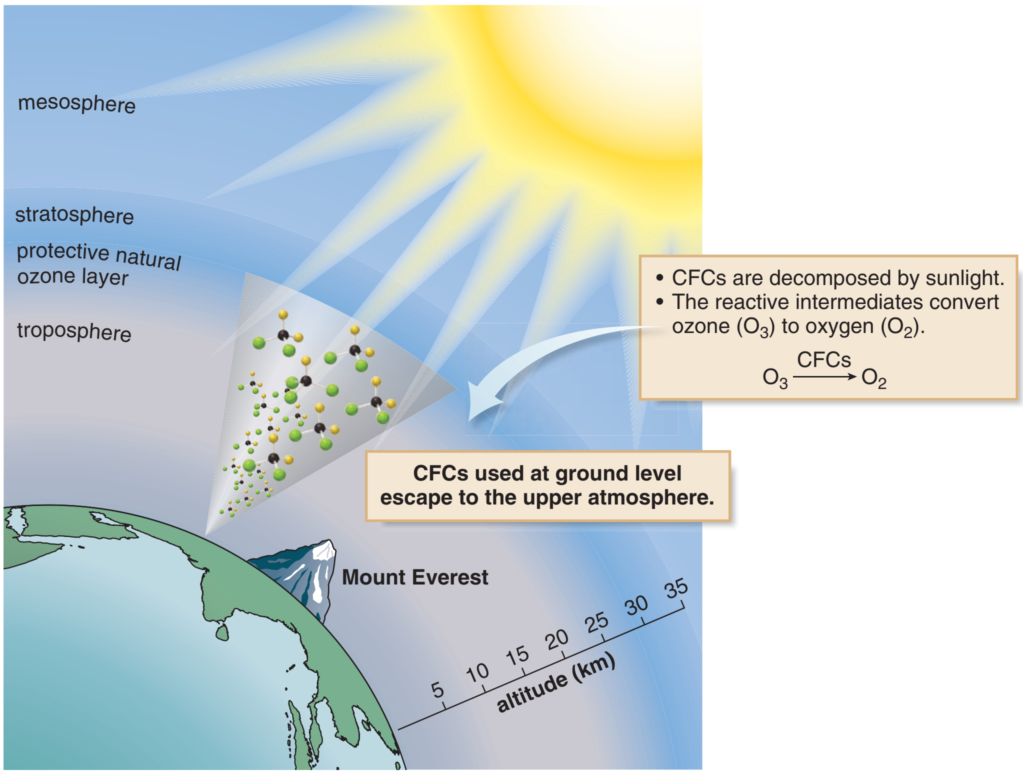
14.9D FOCUS ON THE ENVIRONMENT ALKYL HALIDES AND THE OZONE LAYER

While the beneficial effects of many organic halides are undisputed, certain synthetic chlorinated organics, such as the **chlorofluorocarbons,** have caused lasting harm to the environment. **Chlorofluorocarbons (CFCs)** are simple halogen-containing compounds having the general molecular structure $\mathbf{CF_xCl_{4-x}}$. CFCs are manufactured under the trade name Freons. Two examples are $\mathbf{CFCl_3}$ (Freon 11) and $\mathbf{CF_2Cl_2}$ (Freon 12).

The 1995 Nobel Prize in Chemistry was awarded to Professors Mario Molina, Paul Crutzen, and F. Sherwood Rowland for their work in elucidating the interaction of ozone with CFCs. What began as a very fundamental research project turned out to have important implications in the practical world.

CFCs are inert and nontoxic, and they have been used as refrigerants, solvents, and aerosol propellants. Because CFCs have low boiling points and are water insoluble, they readily escape into the upper atmosphere. There, CFCs are decomposed by sunlight. This process forms highly reactive intermediates that have been shown to destroy the ozone layer (Figure 14.6).

FIGURE 14.6 CFCs and Ozone Destruction

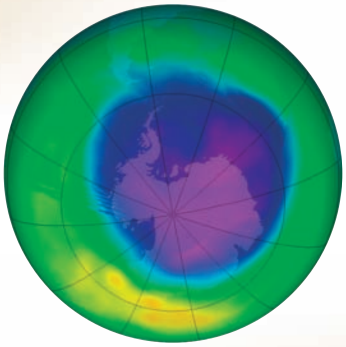


ENVIRONMENTAL NOTE



Propane and butane are now used as propellants in spray cans in place of CFCs.

ENVIRONMENTAL NOTE



O_3 destruction is most severe in the region of the South Pole, where a large ozone hole (shown in purple) is visible with satellite imaging.

The ozone (O_3) in the upper atmosphere is vital to life: it acts as a shield, protecting the earth's surface from destructive ultraviolet radiation. A decrease in ozone concentration in this protective layer will have some immediate consequences, including an increase in the incidence of skin cancer and eye cataracts. Other long-term effects include a reduced immune response, interference with photosynthesis in plants, and harmful effects on the growth of plankton, the mainstay of the ocean food chain.

These findings led to a ban on the use of CFCs in aerosol propellants in the United States in 1978 and to the phasing out of their use in refrigeration systems. While it is now easy to second-guess the extensive use of CFCs, it is also easy to see why they were used so widely. **CFCs made refrigeration available to the general public.** Would you call your refrigerator a comfort or a necessity?

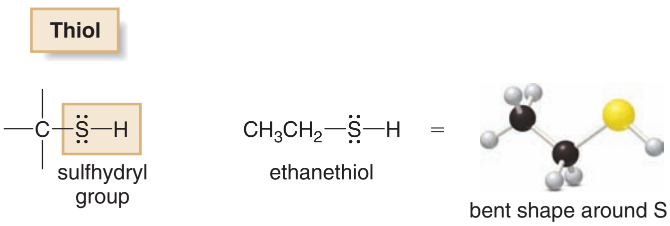
There are two newer alternatives to CFCs. **Hydrochlorofluorocarbons (HCFCs)** such as CF_3CHCl_2 contain the elements of H, Cl, and F bonded to carbon, and **hydrofluorocarbons (HFCs)** such as FCH_2CF_3 contain the elements of H and F bonded to carbon. These compounds have many properties in common with CFCs, but they are decomposed more readily before they reach the upper atmosphere, so they are less destructive to the O_3 layer.

PROBLEM 14.25

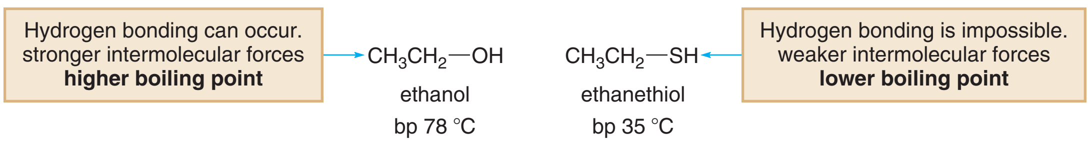
Classify each compound as a CFC, HCFC, or HFC: (a) CF_3Cl; (b) $CHFCl_2$; (c) CH_2F_2.

14.10 ORGANIC COMPOUNDS THAT CONTAIN SULFUR

Thiols **are organic compounds that contain a sulfhydryl group (SH group) bonded to a tetrahedral carbon.** Since sulfur is directly below oxygen in the periodic table, thiols can be considered sulfur analogues of alcohols. Because the sulfur atom is surrounded by two atoms and two lone pairs, thiols have a bent shape around sulfur.

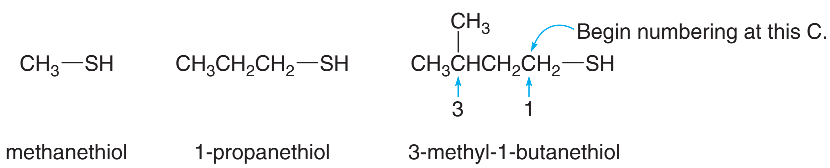


Thiols differ from alcohols in one important way. They contain no O—H bonds, so they are incapable of intermolecular hydrogen bonding. **This gives thiols lower boiling points and melting points compared to alcohols having the same size and shape.**



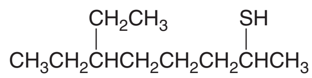
To name a thiol in the IUPAC system:

- Name the parent hydrocarbon as an alkane and add the suffix *-thiol.*
- Number the carbon chain to give the SH group the lower number.



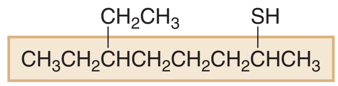
SAMPLE PROBLEM 14.7

Give the IUPAC name for the following thiol.



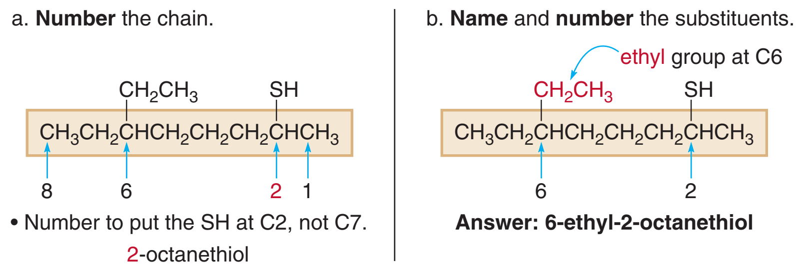
ANALYSIS AND SOLUTION

[1] **Find the longest carbon chain that contains the carbon bonded to the SH group.**



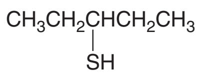
- Name the alkane and add the suffix *-thiol*: **octanethiol.**

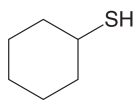
[2] **Number the carbon chain to give the SH group the lower number and apply all other rules of nomenclature.**



PROBLEM 14.26

Give the IUPAC name for each thiol.

a. 

b. 

c. $(CH_3CH_2)_2CHCH_2CH_2CH_2CH_2SH$

PROBLEM 14.27

Skunk odor contains *trans*-2-butene-1-thiol. Draw the structure of this thiol.

The most obvious physical property of thiols is their distinctive foul odor. 1-Propanethiol ($CH_3CH_2CH_2SH$) is partly responsible for the characteristic odor of onions. 3-Methyl-1-butanethiol [$(CH_3)_2CHCH_2CH_2SH$] is one of the main components of the defensive spray of skunks.

Thiols undergo one important reaction: **thiols are oxidized to disulfides,** compounds that contain a sulfur–sulfur bond. This is an oxidation reaction because two hydrogen atoms are removed in forming the disulfide.

Oxidation $2\ CH_3CH_2{-}S{-}H \xrightarrow{[O]} CH_3CH_2{-}S{-}S{-}CH_2CH_3$

thiol → disulfide (new S—S bond)

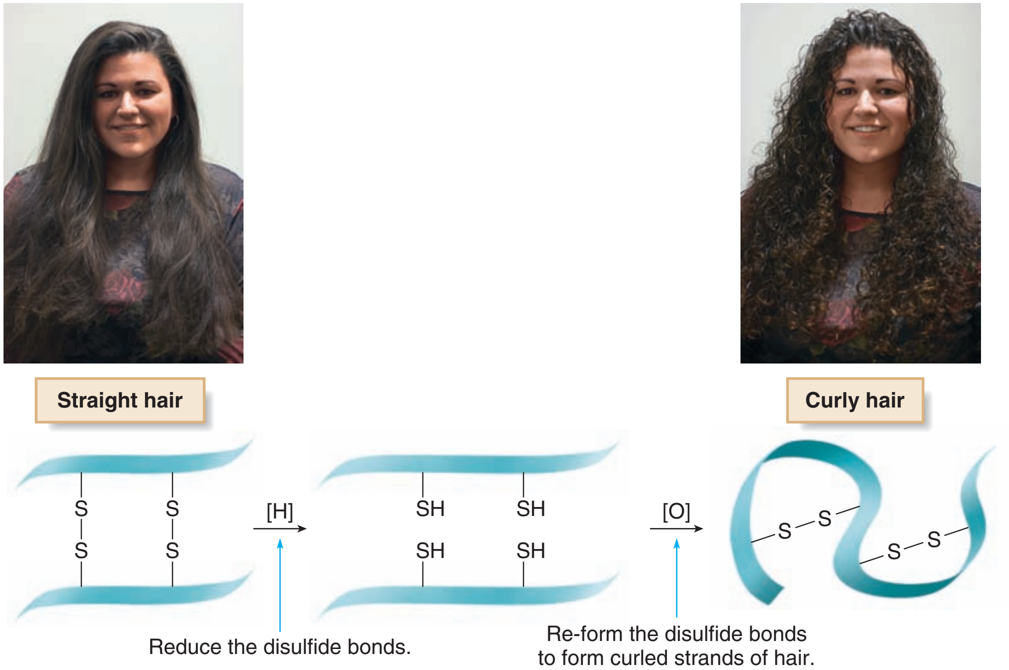
Disulfides can also be converted back to thiols with a reducing agent. The symbol for a general reducing agent is **[H],** since hydrogen atoms are often added to a molecule during reduction.

Reduction $CH_3CH_2{-}S{-}S{-}CH_2CH_3 \xrightarrow{[H]} 2\ CH_3CH_2{-}S{-}H$

disulfide → thiol (new S—H bond)

The chemistry of thiols and disulfides plays an important role in determining the properties and shape of some proteins, as we will learn in Chapter 21. For example, α-keratin, the protein in hair, contains many disulfide bonds. Straight hair can be made curly by cleaving the disulfide bonds in α-keratin, then rearranging and re-forming them, as shown schematically in Figure 14.7.

FIGURE 14.7 Focus on the Human Body: Making Straight Hair Curly



To make straight hair curly, the disulfide bonds holding the protein chains together are reduced. This forms free SH groups. The hair is turned around curlers and then an oxidizing agent is applied. This re-forms the disulfide bonds to the hair, now giving it a curly appearance.

First, the disulfide bonds in the straight hair are reduced to thiol groups, so the bundles of α-keratin chains are no longer held in their specific "straight" orientation. Then, the hair is wrapped around curlers and treated with an oxidizing agent that converts the thiol groups back to disulfide bonds, now with twists and turns in the keratin backbone. This makes the hair look curly and is the chemical basis for a "permanent."

PROBLEM 14.28

(a) Draw the disulfide formed when $CH_3CH_2CH_2SH$ is oxidized. (b) Draw the product formed when the following disulfide is reduced: $CH_3CH_2CH_2CH_2SSCH_2CH_3$.

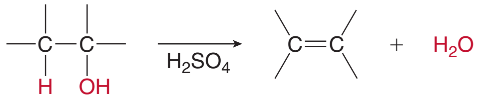
CHAPTER HIGHLIGHTS

KEY TERMS

Alcohol (14.1)
Alkoxy group (14.7)
Alkyl halide (14.1)
Carbonyl group (14.5)
Chlorofluorocarbon (14.9)
Coenzyme (14.6)
Dehydration (14.5)
Diol (14.3)
Disulfide (14.10)
Elimination (14.5)
Epoxide (14.7)
Ether (14.1)
Glycol (14.3)
Heterocycle (14.7)
Hydrochlorofluorocarbon (14.9)
Hydrofluorocarbon (14.9)
Hydroxyl group (14.1)
Oxidation (14.5)
Primary (1°) alcohol (14.2)
Primary (1°) alkyl halide (14.9)
Secondary (2°) alcohol (14.2)
Secondary (2°) alkyl halide (14.9)
Sulfhydryl group (14.1)
Tertiary (3°) alcohol (14.2)
Tertiary (3°) alkyl halide (14.9)
Thiol (14.1)
Triol (14.3)
Zaitsev rule (14.5)

KEY REACTIONS

[1] Dehydration of alcohols (14.5A)



[2] Oxidation of alcohols (14.5B)

a. Primary (1°) alcohols

$RCH_2OH \xrightarrow{[O]} RCHO \xrightarrow{[O]} RCOOH$

RCHO: aldehyde; RCOOH: carboxylic acid

b. Secondary (2°) alcohols

$R_2CHOH \xrightarrow{[O]} R_2CO$

R_2CO: ketone

c. Tertiary (3°) alcohols

$R_3COH \xrightarrow{[O]}$ No reaction

[3] Oxidation of thiols and reduction of disulfides (14.10)

$$2\ R{-}S{-}H \underset{[H]}{\overset{[O]}{\rightleftharpoons}} R{-}S{-}S{-}R$$

thiol → disulfide

KEY CONCEPTS

1 What are the characteristics of alcohols, ethers, alkyl halides, and thiols?

- Alcohols contain a hydroxyl group (OH group) bonded to a tetrahedral carbon. Since the O atom is surrounded by two atoms and two lone pairs, alcohols have a bent shape around O. (14.2)
- Ethers have two alkyl groups bonded to an oxygen atom. Since the O atom is surrounded by two atoms and two lone pairs, ethers have a bent shape around O. (14.7)
- Alkyl halides contain a halogen atom (X = F, Cl, Br, I) singly bonded to a tetrahedral carbon. (14.9)
- Thiols contain a sulfhydryl group (SH group) bonded to a tetrahedral carbon. Since the S atom is surrounded by two atoms and two lone pairs, thiols have a bent shape around S. (14.10)

2 How are alcohols and alkyl halides classified?

- Alcohols and alkyl halides are classified by the number of C's bonded to the C with the functional group.
- RCH_2OH = 1° alcohol; R_2CHOH = 2° alcohol; R_3COH = 3° alcohol. (14.2)
- RCH_2X = 1° alkyl halide; R_2CHX = 2° alkyl halide; R_3CX = 3° alkyl halide. (14.9)

3 What are the properties of alcohols, ethers, alkyl halides, and thiols?

- Alcohols have a bent shape and polar C—O and O—H bonds, so they have a net dipole. Their OH bond allows for intermolecular hydrogen bonding between two alcohol molecules or between an alcohol molecule and water. As a result, alcohols have the strongest intermolecular forces of the four families of molecules in this chapter. (14.2)
- Ethers have a bent shape and two polar C—O bonds, so they have a net dipole. (14.7)
- Alkyl halides with one halogen have one polar bond and a net dipole. (14.9)
- Thiols have a bent shape and lower boiling points than alcohols with the same number of carbons. (4.10)

4 How are alcohols, ethers, alkyl halides, and thiols named?

- Alcohols are identified by the suffix *-ol.* (14.3)
- Ethers are named in two ways. Simple ethers are named by naming the alkyl groups bonded to the ether oxygen and adding the word *ether.* More complex ethers are named as *alkoxy alkanes;* that is, the simpler alkyl group is named as an alkoxy group (RO) bonded to an alkane. (14.7B)
- Alkyl halides are named as *halo alkanes;* that is, the halogen is named as a substituent (halo group) bonded to an alkane. (14.9B)
- Thiols are identified by the suffix *-thiol.* (14.10)

5 What products are formed when an alcohol undergoes dehydration? (14.5A)

- Alcohols form alkenes on treatment with strong acid. The elements of H and OH are lost from two adjacent atoms and a new double bond is formed.
- Dehydration follows the Zaitsev rule: When more than one alkene can be formed, the major product of elimination is the alkene that has more alkyl groups bonded to it.

❻ **What products are formed when an alcohol is oxidized? (14.5B)**

- Primary alcohols (RCH_2OH) are oxidized to aldehydes (RCHO), which are further oxidized to carboxylic acids (RCO_2H).
- Secondary alcohols (R_2CHOH) are oxidized to ketones.
- Tertiary alcohols have no C—H bond on the carbon with the OH group, so they are not oxidized.

❼ **What product is formed when a thiol is oxidized? (14.10)**

- Thiols (RSH) are oxidized to disulfides (RSSR).
- Disulfides are reduced to thiols.

PROBLEMS

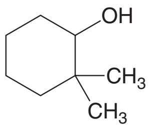
Selected in-chapter and end-of-chapter problems have brief answers provided in Appendix B.

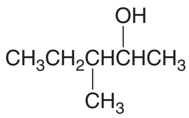
Alcohols, Ethers, Alkyl Halides, and Thiols

14.29 Classify each alcohol as 1°, 2°, or 3°.

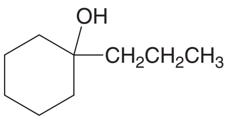
a. $CH_3CH_2CH_2OH$

b. $(CH_3CH_2)_3COH$

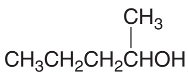
c. 

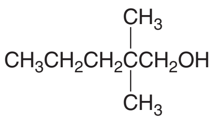
d. 

14.30 Classify each alcohol as 1°, 2°, or 3°.

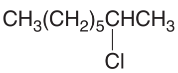
a. 

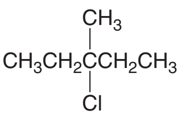
b. $(CH_3)_3CCH_2CH_2OH$

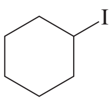
c. 

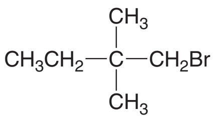
d. 

14.31 Classify each alkyl halide as 1°, 2°, or 3°.

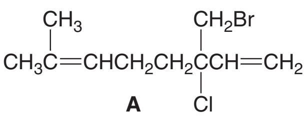
a. 

b. 

c. 

d. 

14.32 Classify each halide in **A** as 1°, 2°, or 3°. **A** is a component of the red seaweed *C. hornemanni* found in Sri Lanka.



A

14.33 Draw the structure of a molecule that fits each description:

a. a 2° alcohol of molecular formula $C_6H_{14}O$

b. an ether with molecular formula $C_6H_{14}O$ that has a methyl group bonded to oxygen

c. a 3° alkyl halide with molecular formula $C_5H_{11}Br$

14.34 Draw the structure of a molecule that fits each description:

a. a 2° alcohol of molecular formula $C_6H_{12}O$

b. a cyclic ether with molecular formula $C_5H_{10}O$

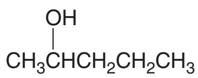
c. a 1° alkyl halide with molecular formula $C_5H_{11}Cl$

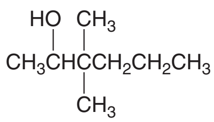
14.35 Draw the structure of the six constitutional isomers of molecular formula $C_5H_{12}O$ that contain an ether as functional group.

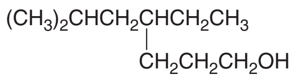
14.36 Draw the structure of the four constitutional isomers of molecular formula $C_3H_6Br_2$.

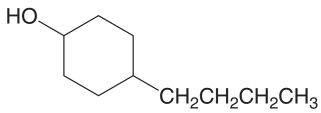
Nomenclature

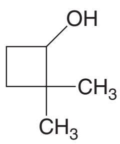
14.37 Give the IUPAC name for each alcohol.

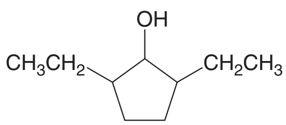
a. 

b. 

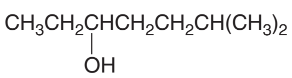
c. 

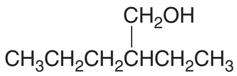
d. 

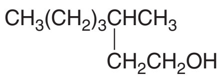
e. 

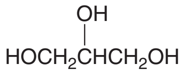
f. 

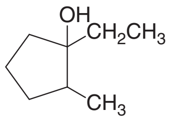
14.38 Give the IUPAC name for each alcohol.

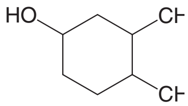
a. 

b. 

c. 

d. 

e. 

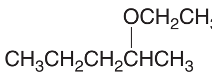
f. 

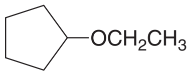
14.39 Give the structure corresponding to each IUPAC name.
a. 3-hexanol
b. propyl alcohol
c. 2-methylcyclopropanol
d. 1,2-butanediol
e. 4,4,5-trimethyl-3-heptanol
f. 3,5-dimethyl-1-heptanol

14.40 Give the structure corresponding to each IUPAC name.
a. 3-methyl-3-pentanol
b. 4-methyl-2-pentanol
c. 2,4-dimethyl-2-hexanol
d. 1,3-propanediol
e. 3,5-dimethylcyclohexanol
f. 6,6-diethyl-4-nonanol

14.41 Give an acceptable name (IUPAC or common) for each ether.

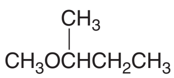
a. $CH_3CH_2OCH_2CH_2CH_2CH_3$

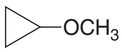
b. 

c. 

14.42 Give an acceptable name (IUPAC or common) for each ether.

a. $CH_3OCH_2CH_2CH_3$

b. 

c. 

14.43 MTBE [$CH_3OC(CH_3)_3$] is a high-octane gasoline additive that has the common name *tert*-butyl methyl ether. What is its IUPAC name?

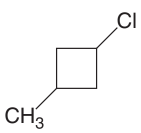
14.44 What is the IUPAC name for diethyl ether?

14.45 Draw the structures and give the IUPAC names for all constitutional isomers of molecular formula $C_7H_{16}O$ that contain an OH group and have seven carbons in the longest chain.

14.46 Draw structures for the four constitutional isomers of molecular formula $C_4H_{10}O$ that contain an OH group. Give the IUPAC name for each alcohol.

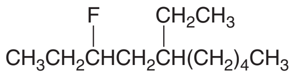
14.47 Give the IUPAC name for each alkyl halide and thiol.

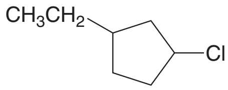
a. $(CH_3CH_2CH_2)_2CHBr$

b. 

c. $CH_3CH_2CH_2CH_2CH_2SH$

14.48 Give the IUPAC name for each alkyl halide and thiol.

a. 

b. 

c. $(CH_3)_2CHSH$

14.49 Give the structure corresponding to each IUPAC name.
a. 2-methoxypropane
b. cyclobutyl ethyl ether
c. 1-ethoxy-2-ethylcyclohexane
d. butyl chloride
e. 2-methylcyclohexanethiol
f. 1-ethyl-2-fluorocyclobutane

14.50 Give the structure corresponding to each IUPAC name.
a. dicyclohexyl ether
b. 2-ethoxy-2-methylpropane
c. propyl iodide
d. 3-methyl-1-pentanethiol
e. 1-chloro-2-methylpropane
f. 2-bromo-3-methylheptane

Physical Properties

14.51 Which compound in each pair has the higher boiling point?
a. $CH_3CH_2CH_2Cl$ or $CH_3CH_2CH_2I$
b. $CH_3CH_2CH_2OH$ or $HOCH_2CH_2OH$
c. $CH_3CH_2CH_2OH$ or $CH_3CH_2CH_2F$

14.52 Rank the compounds in each group in order of increasing boiling point.
a. $CH_3CH_2OCH_2CH_3$, $CH_3(CH_2)_3CH_3$, $CH_3CH_2CH_2CH_2OH$
b. $CH_3CH_2CH_2CH_2OH$, $CH_3CH_2CH_2OH$, CH_3CH_2OH
c. $CH_3CH_2CH_2CH_2OH$, $CH_3CH_2CH_2CH_3$, $CH_3CH_2CH_2CH_2Cl$

14.53 Explain the following observation. Dimethyl ether [$(CH_3)_2O$] and ethanol (CH_3CH_2OH) are both water-soluble compounds. The boiling point of ethanol (78 °C), however, is much higher than the boiling point of dimethyl ether (–24 °C).

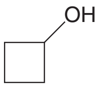
14.54 Explain why the boiling point of $CH_3CH_2CH_2CH_2OH$ (117 °C) is higher than the boiling point of $CH_3CH_2CH_2CH_2SH$ (98 °C), even though $CH_3CH_2CH_2CH_2SH$ has a higher molecular weight.

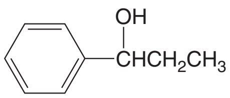
14.55 Explain why two four-carbon organic molecules have very different solubility properties: 1-butanol ($CH_3CH_2CH_2CH_2OH$) is water soluble but 1-butene ($CH_2{=}CHCH_2CH_3$) is water insoluble.

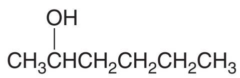
14.56 Explain why 1,6-hexanediol [$HO(CH_2)_6OH$] is much more water soluble than 1-hexanol [$CH_3(CH_2)_5OH$].

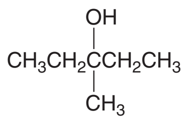
Reactions of Alcohols

14.57 Draw the products formed when each alcohol is dehydrated with H_2SO_4. Use the Zaitsev rule to predict the major product when a mixture forms.

a. 

b. 

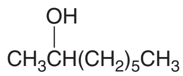
c. 

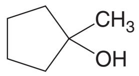
d. 

14.58 Draw the products formed when each alcohol is dehydrated with H_2SO_4. Use the Zaitsev rule to predict the major product when a mixture forms.

a. $(CH_3)_2CHCH_2CH_2CH_2OH$

b. $(CH_3CH_2)_3COH$

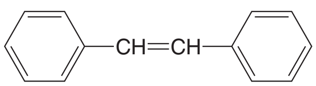
c. 

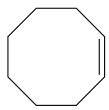
d. 

14.59 Dehydration of 3-hexanol [$CH_3CH_2CH(OH)CH_2CH_2CH_3$] yields a mixture of two alkenes. (a) Draw the structures of both constitutional isomers formed. (b) Use the Zaitsev rule to explain why both products are formed in equal amounts.

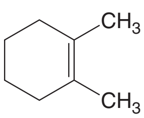
14.60 Dehydration of 3-methylcyclohexanol yields a mixture of two alkenes. (a) Draw the structures of both constitutional isomers formed. (b) Use the Zaitsev rule to explain why both products are formed in equal amounts.

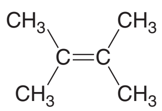
14.61 What alcohol is needed to form each alkene as a product of a dehydration reaction?

a. 

b. 

14.62 What alcohol is needed to form each alkene as the major product of a dehydration reaction?

a. 

b. 

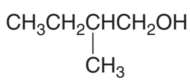
14.63 Propene ($CH_3CH{=}CH_2$) can be formed by dehydrating two different alcohols. Draw the structures of both alcohols.

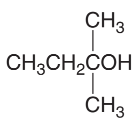
14.64 2-Methylpropene [$(CH_3)_2C{=}CH_2$] can be formed by dehydrating two different alcohols. Draw the structures of both alcohols.

14.65 Draw the products formed when each alcohol is oxidized with $K_2Cr_2O_7$. In some cases, no reaction occurs.

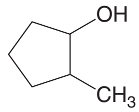
a. $CH_3(CH_2)_6CH_2OH$

b. $(CH_3CH_2)_2CHOH$

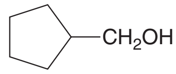
c. 

d. 

14.66 Draw the products formed when each alcohol is oxidized with $K_2Cr_2O_7$. In some cases, no reaction occurs.

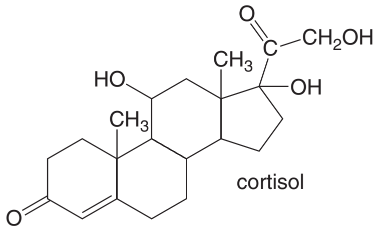
a. 

b. $CH_3(CH_2)_8CH_2OH$

c. 

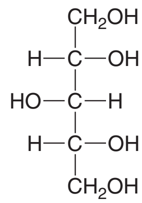
d. $(CH_3CH_2)_3COH$

14.67 Cortisol is an anti-inflammatory agent that also regulates carbohydrate metabolism. What oxidation product is formed when cortisol is treated with $K_2Cr_2O_7$?



cortisol

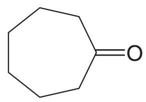
14.68 Xylitol is a nontoxic compound as sweet as table sugar but with only one-third the calories, so it is often used as a sweetening agent in gum and hard candy.

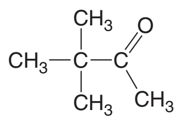


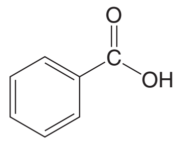
xylitol

a. Classify the OH groups as 1°, 2°, or 3°.
b. What product is formed when only the 1° OH groups are oxidized?
c. What product is formed when all of the OH groups are oxidized?

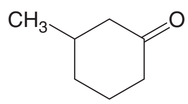
14.69 What alcohol starting material is needed to prepare each carbonyl compound as a product of an oxidation reaction?

a. 

b. 

c. 

14.70 What alcohol starting material is needed to prepare each carbonyl compound as a product of an oxidation reaction?

a. 

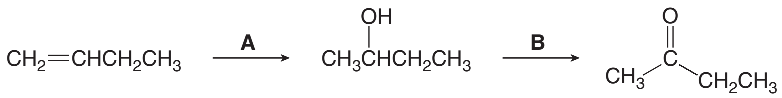
b. $CH_3CH_2CH_2CH_2CH_2CO_2H$

c. $(CH_3CH_2)_2C{=}O$

14.71 What products are formed when 4-heptanol $[(CH_3CH_2CH_2)_2CHOH]$ is treated with each reagent: (a) H_2SO_4; (b) $K_2Cr_2O_7$?

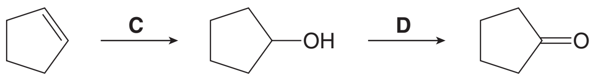
14.72 What products are formed when 2-methyl-4-heptanol $[(CH_3)_2CHCH_2CH(OH)CH_2CH_2CH_3]$ is treated with each reagent: (a) H_2SO_4; (b) $K_2Cr_2O_7$?

14.73 Often there is no one-step method to convert one organic compound into another. Instead, two or more steps must be carried out. For example, 1-butene is converted to 2-butanone by the two-step reaction sequence drawn below. Fill in the reagents (**A** and **B**) needed to carry out each step.



1-butene 2-butanol 2-butanone

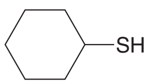
14.74 Fill in the reagents (**C** and **D**) needed to convert each starting material to the product drawn. This two-step reaction sequence is used to convert an alkene like cyclopentene to a ketone like cyclopentanone, as shown.



cyclopentene cyclopentanol cyclopentanone

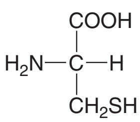
Reactions of Thiols

14.75 What disulfide is formed when each thiol is oxidized?

a. 

b. $CH_3(CH_2)_4SH$

14.76 As we will learn in Chapter 21, cysteine is a naturally occurring amino acid that contains a thiol group. What disulfide is formed when cysteine is oxidized?

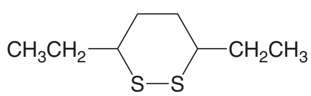


cysteine

14.77 The smell of fried onions is in part determined by the two disulfides drawn below. What thiols are formed when each disulfide is reduced?

a. $CH_3S—SCH_2CH_2CH_3$ b. $CH_2=CHCH_2S—SCH_2CH_2CH_3$

14.78 Sometimes disulfide bonds occur in a ring. As we will learn in Chapter 21, these disulfide bonds play an important role in determining the shape and properties of proteins. What *di*thiol is formed when the following disulfide is reduced?



Applications

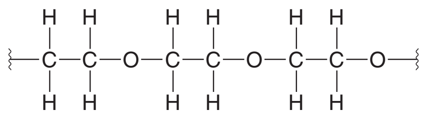
14.79 Diethyl ether $[(CH_3CH_2)_2O]$ is an imperfect anesthetic in part because it readily combusts in air to form CO_2 and H_2O. Write a balanced equation for the complete combustion of diethyl ether.

14.80 Methanol (CH_3OH) is used as a fuel for some types of race cars, because it readily combusts in air to form CO_2 and H_2O. Write a balanced equation for the complete combustion of methanol.

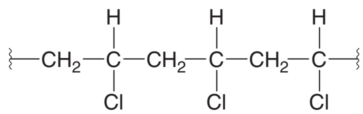
14.81 With reference to the halogenated organic compounds called CFCs, HCFCs, and HFCs: (a) How do these compounds differ in structure? (b) How do these compounds differ in their interaction with ozone?

14.82 Give an example of a CFC and explain why the widespread use of CFCs has been detrimental to the environment.

14.83 As we learned in Chapter 13, polymers have very different properties depending (in part) on their functional groups. For example, poly(ethylene glycol) is commonly used in shampoos, where it forms viscous solutions in water. Poly(vinyl chloride), on the other hand, repels water and is used to make pipes and garden hoses. Discuss the water solubility of these polymers, and explain why there is a difference, even though both polymers have several polar bonds.



poly(ethylene glycol)
PEG

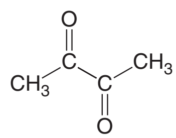


poly(vinyl chloride)
PVC

14.84 Give an example of a halogenated ether commonly used as an anesthetic. Give two reasons why halogenated ethers are now used in place of diethyl ether as anesthetics.

14.85 Write out the chemical reaction that occurs when a breathalyzer test is carried out. How does this test give an indication of blood alcohol content?

14.86 2,3-Butanedione is commonly used to give microwave popcorn a buttery flavor. What diol is needed to prepare 2,3-butanedione by an oxidation reaction?



2,3-butanedione
(butter flavor)

14.87 In contrast to ethylene glycol ($HOCH_2CH_2OH$), which is extremely toxic, propylene glycol [$CH_3CH(OH)CH_2OH$] is nontoxic because it is oxidized in the body to a product produced during the metabolism of carbohydrates. What product is formed when propylene glycol is oxidized?

14.88 Lactic acid [$CH_3CH(OH)CO_2H$] gives sour milk its distinctive taste. What product is formed when lactic acid is oxidized by $K_2Cr_2O_7$?

14.89 Write out the chemical reactions that occur during the metabolism of ethanol. Explain how Antabuse is used in the treatment of alcoholism.

14.90 What chemical reactions occur when straight hair is made curly with a "permanent"?

General Questions

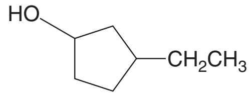
14.91 An unknown alcohol of molecular formula $C_4H_{10}O$ forms only one alkene when treated with H_2SO_4. No reaction is observed when the alcohol is treated with an oxidizing agent. Draw the structure of the alcohol.

14.92 You have two test tubes, one containing $(CH_3CH_2)_3COH$ and one containing $CH_3(CH_2)_6OH$, but you do not know which alcohol is in which tube. Explain how treating the alcohols with an oxidizing agent like $K_2Cr_2O_7$ can help you to determine which test tube contains which alcohol.

14.93 Explain why two ether molecules can't hydrogen bond to each other, but an ether molecule can hydrogen bond to a water molecule.

14.94 When an alcohol hydrogen bonds with water, two different hydrogen bonding interactions are possible. The oxygen atom of the alcohol (ROH) can hydrogen bond with a hydrogen atom of water, or a hydrogen atom of the alcohol can hydrogen bond to the oxygen atom of water. Illustrate both of these possibilities with CH_3CH_2OH.

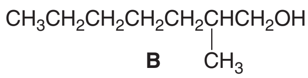
14.95 Answer the following questions about alcohol **A.**



A

a. Give the IUPAC name.
b. Classify the alcohol as 1°, 2°, or 3°.
c. Draw the products formed when **A** is dehydrated with H_2SO_4.
d. What product is formed when **A** is oxidized with $K_2Cr_2O_7$?
e. Draw a constitutional isomer of **A** that contains an OH group.
f. Draw a constitutional isomer of **A** that contains an ether.

14.96 Answer the following questions about alcohol **B.**



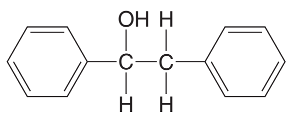
B

a. Give the IUPAC name.
b. Classify the alcohol as 1°, 2°, or 3°.
c. Draw the products formed when **B** is dehydrated with H_2SO_4.
d. What product is formed when **B** is oxidized with $K_2Cr_2O_7$?
e. Draw a constitutional isomer of **B** that contains an OH group.
f. Draw a constitutional isomer of **B** that contains an ether.

CHALLENGE QUESTIONS

14.97 2-Methyl-1-butene can be formed by dehydrating two different alcohols (**A** and **B**) of molecular formula ($C_5H_{12}O$). When **A** undergoes dehydration, 2-methyl-1-butene is formed as the *only* product of dehydration. When alcohol **B** undergoes dehydration, two different alkenes are formed and 2-methyl-1-butene is formed as the *minor* product. (a) Identify the structures of **A** and **B.** (b) What is the major alkene formed when **B** undergoes dehydration?

14.98 Dehydration of alcohol **C** forms two products of molecular formula $C_{14}H_{12}$ that are isomers, but they are not constitutional isomers. Draw the structures of these two products.



C

15

CHAPTER OUTLINE

CHAPTER GOALS

In this chapter you will learn how to:

1. Recognize whether a molecule is chiral or achiral
2. Identify chirality centers
3. Draw two enantiomers in three dimensions around the chirality center
4. Explain why some chiral drugs have very different properties from their mirror images
5. Draw Fischer projection formulas
6. Recognize the difference between enantiomers and diastereomers
7. Explain the relationship between the shape and odor of a molecule



Naproxen is the active ingredient in the widely used pain relievers Naprosyn and Aleve. The three-dimensional arrangement of two atoms on a single carbon atom in naproxen determines its therapeutic properties.

THE THREE-DIMENSIONAL SHAPE OF MOLECULES

ARE you left-handed or right-handed? If you're right-handed, you've probably spent little time thinking about your hand preference. If you're left-handed, though, you probably learned at an early age that many objects—like scissors and baseball gloves—"fit" for righties, but are "backwards" for lefties. **Hands, like many objects in the world around us, are mirror images that are *not* identical.** In Chapter 15 we examine the "handedness" of molecules, and ask, "How important is the three-dimensional shape of a molecule?"

15.1 ISOMERS—A REVIEW

Chapter 15 concentrates on ***stereochemistry*—that is, the three-dimensional structure of molecules.** Since an understanding of isomers is needed in the discussion of stereochemistry, let's begin with an overview of isomers. Recall from Section 12.2:

- **Isomers are different compounds with the same molecular formula.**

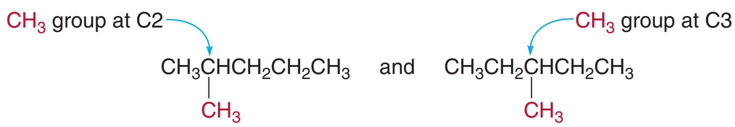
There are two major classes of isomers: **constitutional isomers** (Section 12.2) and **stereoisomers** (Section 13.3).

- ***Constitutional isomers* differ in the way the atoms are connected to one another.**

Constitutional isomers have atoms bonded to *different* atoms. As a result, constitutional isomers have different IUPAC names. Constitutional isomers may have the same functional group or they may have different functional groups.

For example, 2-methylpentane and 3-methylpentane are constitutional isomers with molecular formula C_6H_{14}. 2-Methylpentane has a CH_3 group bonded to the second atom (C2) of a five-carbon chain, while 3-methylpentane has a CH_3 group bonded to the middle atom (C3) of a five-carbon chain. Both molecules are alkanes, so they both belong to the same family of organic compounds.

Constitutional isomers with the same functional group



2-methylpentane C_6H_{14} | **3**-methylpentane C_6H_{14}

Ethanol and dimethyl ether are constitutional isomers with molecular formula C_2H_6O. Ethanol contains an O—H bond and dimethyl ether does not. Thus, the atoms are bonded to different atoms and these constitutional isomers have *different* functional groups. Dimethyl ether is an ether and ethanol is an alcohol.

Constitutional isomers with different functional groups

CH_3CH_2—O—H — ethanol, C_2H_6O

CH_3—O—CH_3 — dimethyl ether, C_2H_6O

- ***Stereoisomers* differ *only* in the three-dimensional arrangement of atoms.**

Stereoisomers always have the *same* functional group, since they differ only in the way the atoms are oriented in space. Two stereoisomers need a prefix like cis or trans added to their IUPAC names to distinguish them. The cis and trans isomers of 2-butene are an example of stereoisomers. Each stereoisomer of 2-butene contains the same sequence of atoms. The only difference is the three-dimensional arrangement of the two methyl groups on the double bond.

One example of stereoisomers—Isomers at a double bond



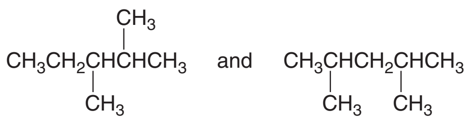
cis-2-butene | *trans*-2-butene

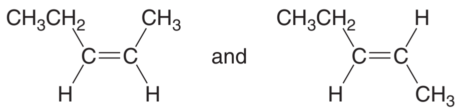
- **The *cis* isomer has the two CH_3 groups on the same side of the double bond.**
- **The *trans* isomer has the two CH_3 groups on opposite sides of the double bond.**

Cis and trans isomers on a carbon–carbon double bond are one example of stereoisomers. In Section 15.2, we learn about another type of stereoisomer that occurs at a tetrahedral carbon.

PROBLEM 15.1

Classify each pair of compounds as identical molecules, constitutional isomers, or stereoisomers.

a. 

b. 

c. $CH_3CH{=}CHCH_2CH_3$ and $CH_3CH_2CH{=}CHCH_3$

d. 

15.2 LOOKING GLASS CHEMISTRY—MOLECULES AND THEIR MIRROR IMAGES

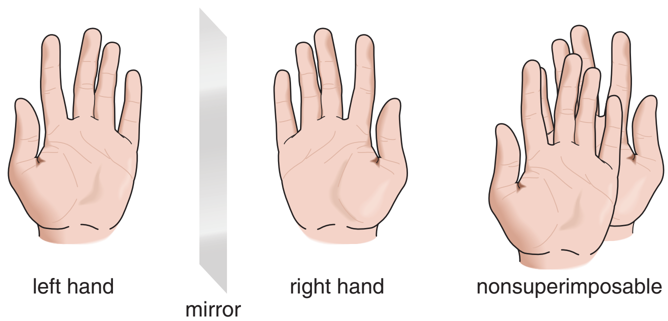
To learn more about stereoisomers that occur at tetrahedral carbon atoms, we must turn our attention to molecules and their mirror images. **Everything, including molecules, has a mirror image.** What's important in chemistry is **whether a molecule is *identical* to or *different* from its mirror image.**

15.2A WHAT IT MEANS TO BE CHIRAL OR ACHIRAL



The dominance of right-handedness over left-handedness occurs in all races and cultures. Despite this fact, even identical twins can exhibit differences in hand preference. Pictured are Matthew (right-handed) and Zachary (left-handed), identical twin sons of the author.

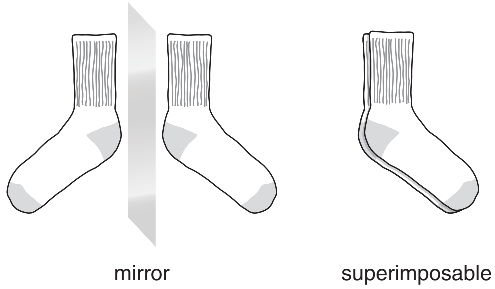
Some molecules are like hands. **Left and right hands are mirror images of each other, but they are *not* identical.** If you try to mentally place one hand inside the other hand you can never superimpose either all the fingers, or the tops and palms. To *superimpose* an object on its mirror image means to align *all* parts of the object with its mirror image. With molecules, this means aligning all atoms and all bonds.



- **A molecule (or object) that is *not* superimposable on its mirror image is said to be *chiral.***

The adjective ***chiral*** (pronounced ky-rel) comes from the Greek *cheir,* meaning *hand.* Left and right hands are **chiral:** they are mirror images that do not superimpose on each other.

Other molecules are like socks. **Two socks from a pair are mirror images that *are* superimposable.** One sock can fit inside another, aligning toes and heels, and tops and bottoms. A sock and its mirror image are *identical.*



- A molecule (or object) that *is* superimposable on its mirror image is said to be *achiral.*

PROBLEM 15.2 Classify each object as chiral or achiral: (a) nail; (b) screw; (c) glove; (d) pencil.

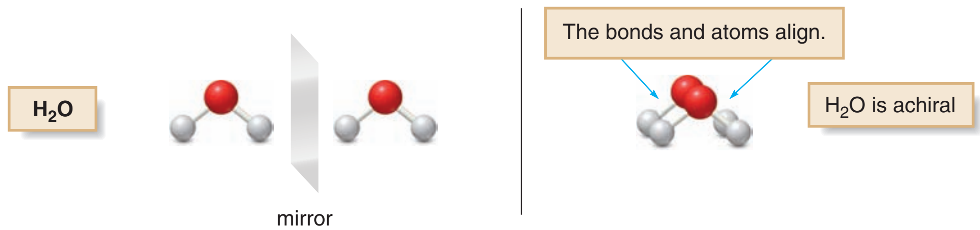
15.2B THE CHIRALITY OF MOLECULES

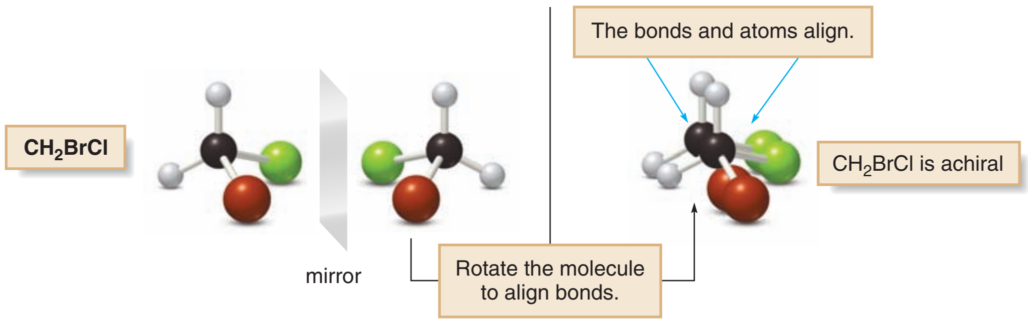
Let's determine whether three molecules—H_2O, CH_2BrCl, and CHBrClF—are superimposable on their mirror images; that is, **are H_2O, CH_2BrCl, and CHBrClF chiral or achiral?**

To test **chirality**—that is, to test whether a molecule and its mirror image are identical or different:

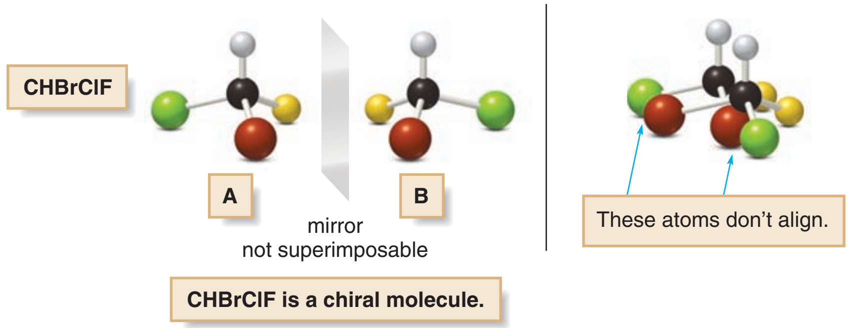
1. Draw the molecule in three dimensions.
2. Draw its mirror image.
3. Try to align all bonds and atoms. To superimpose a molecule and its mirror image you can perform any rotation but **you cannot break bonds.**

Following this procedure, H_2O and CH_2BrCl are both **achiral** molecules: each molecule is superimposable on its mirror image.





With CHBrClF, the result is different. The molecule (labeled **A)** and its mirror image (labeled **B)** are not superimposable. No matter how you rotate **A** and **B,** all of the atoms never align. **CHBrClF is thus a chiral molecule,** and **A** and **B** are different compounds.



A and **B** are **stereoisomers** since they are isomers differing only in the three-dimensional arrangement of substituents. They represent a new type of stereoisomer that occurs at tetrahedral carbon atoms. These stereoisomers are called ***enantiomers.***

- Enantiomers are mirror images that are not superimposable.

Naming a carbon atom with four different groups is a topic that currently has no firm agreement among organic chemists. IUPAC recommends the term *chirality center,* and so this is the term used in this text. Other terms in common use are chiral center, chiral carbon, asymmetric carbon, and stereogenic center.

CHBrClF contains a carbon atom bonded to four different groups. **A carbon atom bonded to four different groups is called a *chirality center.***

We have now learned two related but different concepts, and it is necessary to distinguish between them.

- A molecule that is not superimposable on its mirror image is a *chiral molecule.*
- A carbon atom surrounded by four different groups is a *chirality center.*

CHBrClF is a chiral molecule because it is not superimposable on its mirror image. CHBrClF contains one chirality center, one carbon atom bonded to four different groups. Molecules can contain zero, one, or more chirality centers.

15.2C CHIRALITY IN NATURE

Why must we study a topic like stereochemistry that may seem so esoteric? In truth, chirality pervades our existence. On a molecular level, many biological molecules discussed in Chapters 19–22 are chiral. On a macroscopic level, many naturally occurring objects possess handedness. Examples include helical seashells shaped like right-handed screws, and plants such as honeysuckle that wind in a left-handed helix (Figure 15.1). The human body is chiral, and hands, feet, and ears are not superimposable.

PROBLEM 15.3 Explain the difference between the terms *chiral* and *chirality center.*

15.3 CHIRALITY CENTERS

A necessary skill in studying the three-dimensional structure of molecules is the ability to locate and draw chirality centers—carbon atoms bonded to four different groups.

15.3A LOCATING CHIRALITY CENTERS

To locate a chirality center, examine each **tetrahedral** carbon atom in a molecule, and look at the four ***groups***—not the four *atoms*—bonded to it. CBrClFI has one chirality center since its carbon

FIGURE 15.1 Chirality in Nature

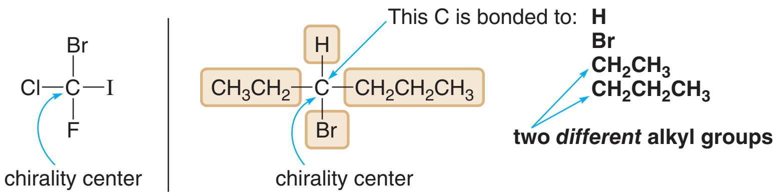
a. b.



a. Many types of snails possess a chiral, right-handed helical shell. When a right-handed shell is held in the right hand with the thumb pointing towards the wider end, the opening is on the right side.

b. Plants like honeysuckle wind in a chiral left-handed helix.

atom is bonded to four different elements—Br, Cl, F, and I. 3-Bromohexane also has one chirality center since one carbon is bonded to H, Br, CH_2CH_3, and $CH_2CH_2CH_3$. We consider all atoms in a group as a *whole unit,* not just the atom directly bonded to the carbon in question.



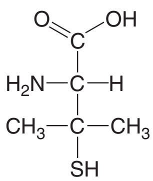
3-bromohexane

Keep in mind the following:

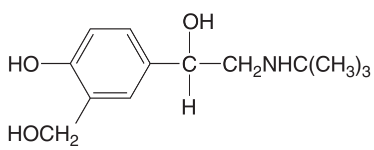
- **A carbon atom bonded to two or more like groups is *never* a chirality center. CH_2 and CH_3 groups have more than one H atom bonded to the same carbon, so each of these carbons is *never* a chirality center.**
- **A carbon that is part of a multiple bond does not have four groups around it, so it can *never* be a chirality center.**

SAMPLE PROBLEM 15.1

Locate the chirality center in each drug.

a. 

penicillamine

b. 

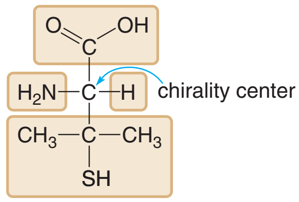
albuterol

ANALYSIS In compounds with many C's, look at each C individually and eliminate those C's that can't be chirality centers. Thus, omit all CH_2 and CH_3 groups and all multiply bonded C's. Check all remaining C's to see if they are bonded to four different groups.

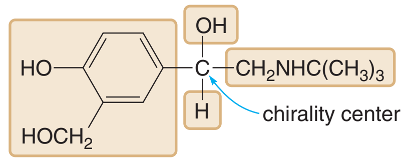
SOLUTION

a. **Penicillamine** is used to treat Wilson's disease, a genetic disorder that leads to a buildup of copper in the liver, kidneys, and the brain. The CH_3 groups and COOH group in penicillamine are not chirality centers. One C is bonded to two CH_3 groups, so it can be eliminated from consideration as well. This leaves one C with four different groups bonded to it.

b. **Albuterol** is a bronchodilator—that is, it widens air passages—so it is used to treat asthma. Omit all CH_2 and CH_3 groups and all C's that are part of a double bond. Also omit from consideration the one C bonded to three CH_3 groups. This leaves one C with four different groups bonded to it.

a. 

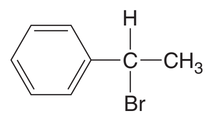
penicillamine

b. 

albuterol

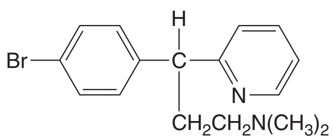
PROBLEM 15.4

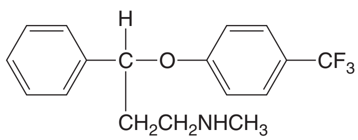
Label the chirality center in the given molecules. The compounds contain zero or one chirality center.

a. $CH_3CH(Cl)CH_2CH_3$ b. $(CH_3)_3CH$ c. $CH_2{=}CHCH(OH)CH_3$ d. 

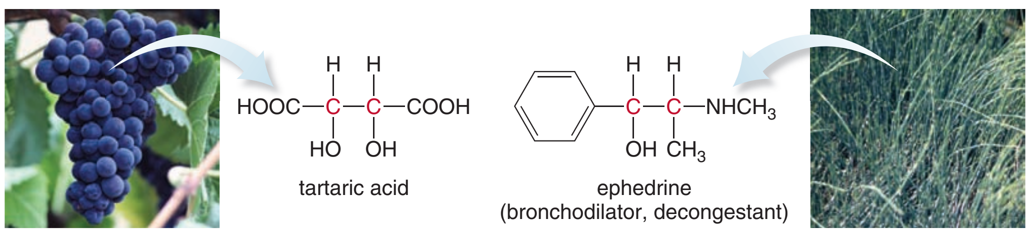
PROBLEM 15.5

Label the chirality center in each drug.

a. 
brompheniramine
(antihistamine)

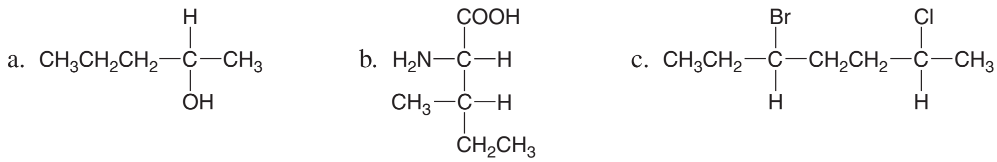
b. 
fluoxetine
Trade name: Prozac
(antidepressant)

Larger organic molecules can have two, three, or even hundreds of chirality centers. Tartaric acid, isolated from grapes, and ephedrine, isolated from the herb ma huang (used to treat respiratory ailments in traditional Chinese medicine), each have two chirality centers. Once a popular drug to promote weight loss and enhance athletic performance, ephedrine use has now been linked to episodes of sudden death, heart attack, and stroke.

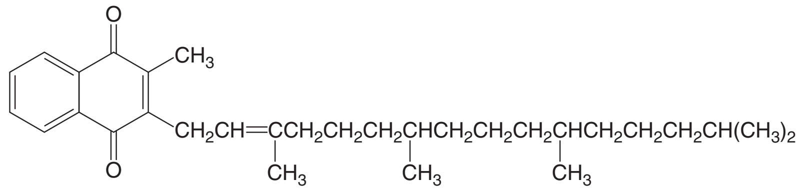


[Chirality centers are labeled in red.]

PROBLEM 15.6 Label the chirality centers in each molecule. Compounds may have one or two chirality centers.



PROBLEM 15.7 Label the two chirality centers in vitamin K. Vitamin K is essential to blood clot formation. A deficiency of this vitamin may lead to excessive and often fatal bleeding.



vitamin K



Lettuce, spinach, broccoli, and cabbage are all excellent sources of vitamin K.

15.3B DRAWING A PAIR OF ENANTIOMERS

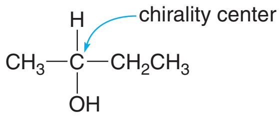
How are chirality centers related to chiral molecules?

- **Any molecule with one chirality center is a chiral compound.**

Recall from Section 15.2 that a **chiral compound is not superimposable on its mirror image,** and that these mirror image isomers are called **enantiomers.** Let's learn how to draw two enantiomers using 2-butanol [$CH_3CH(OH)CH_2CH_3$], a compound with one chirality center, as an example.

HOW TO Draw Two Enantiomers of a Chiral Compound

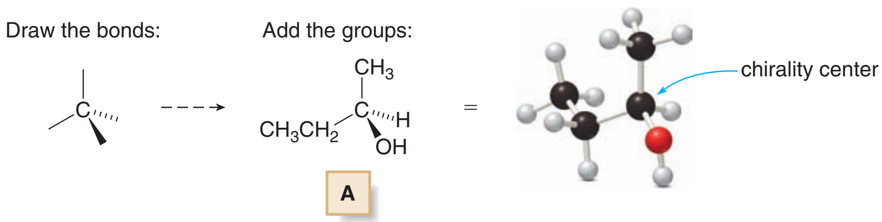
EXAMPLE **Draw two enantiomers of 2-butanol in three dimensions around the chirality center.**



2-butanol

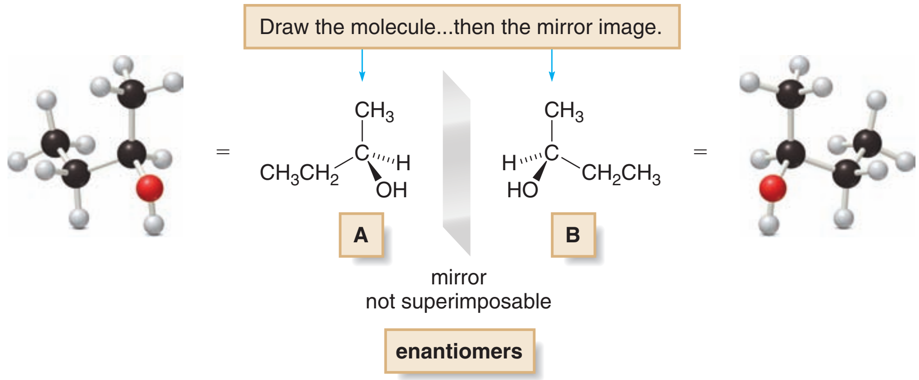
Step [1] **Draw one enantiomer by arbitrarily placing the four different groups on any bond to the chirality center.**

- Use the convention learned in Section 11.3 for drawing a tetrahedron: **place two bonds in the plane, one in front of the plane on a wedge, and one behind the plane on a dashed line.**
- Arbitrarily place the four groups—H, OH, CH_3, and CH_2CH_3—on any bond to the chirality center, forming enantiomer **A.**



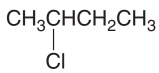
Step [2] **Draw a mirror plane and arrange the substituents in the mirror image so that they are a reflection of the groups in the first molecule.**

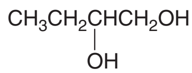
- Place the four groups—H, OH, CH_3, and CH_2CH_3—on the chirality center in the mirror image to form enantiomer **B.**
- **A** and **B** are mirror images, but no matter how **A** and **B** are rotated their bonds do not align, so **A** and **B** are chiral compounds.



PROBLEM 15.8

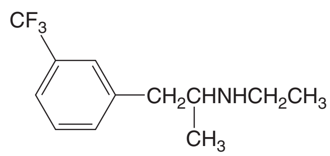
Locate the chirality center in each compound and draw both enantiomers.

a. 

b. 

PROBLEM 15.9

Locate the chirality center and draw both enantiomers of fenfluramine, one component of the appetite suppressant Fen–Phen (see also Problem 11.32).



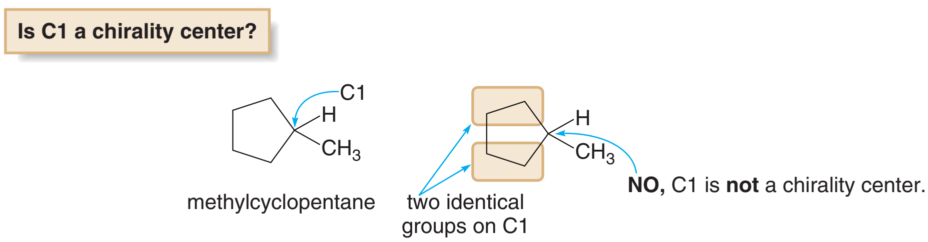
fenfluramine

15.4 CHIRALITY CENTERS IN CYCLIC COMPOUNDS

Chirality centers may also occur at carbon atoms that are part of a ring. To find chirality centers on ring carbons, always draw the rings as flat polygons, and look for tetrahedral carbons that are bonded to four different groups, as usual.

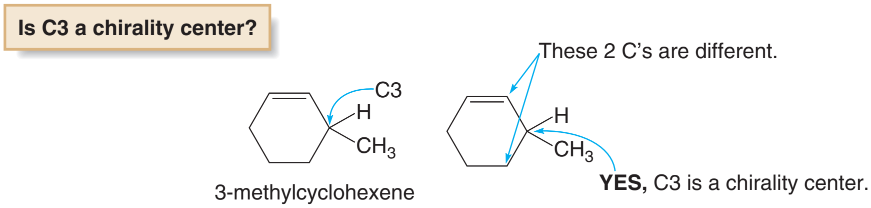
15.4A LOCATING CHIRALITY CENTERS ON RING CARBONS

Does methylcyclopentane have a chirality center?



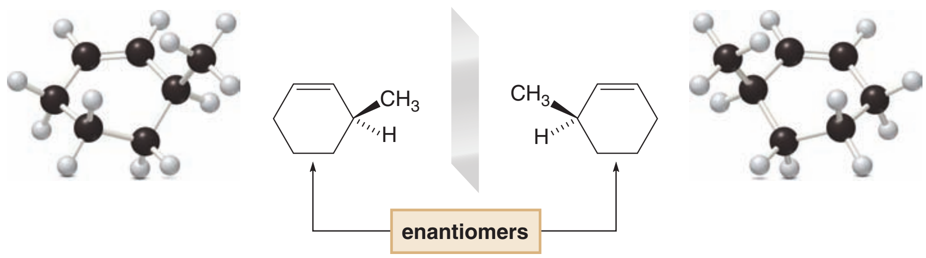
All of the carbon atoms are bonded to two or three hydrogen atoms except for C1, the ring carbon bonded to the methyl group. Next, compare the ring atoms and bonds on both sides the same distance from C1, and continue until a point of difference is reached, or until both sides meet. In this case, there is no point of difference on either side, so C1 is considered to be bonded to identical alkyl groups that happen to be part of a ring. **C1 is therefore *not* a chirality center.**

With 3-methylcyclohexene, the result is different.



All carbon atoms are bonded to two or three hydrogen atoms or are part of a double bond except for C3, the ring carbon bonded to the methyl group. In this case, the atoms equidistant from C3 are different, so C3 is considered to be bonded to *different* alkyl groups in the ring. **C3 is therefore bonded to four different groups, making it a chirality center.**

Since 3-methylcyclohexene has one tetrahedral chirality center, it is a chiral compound, and exists as a pair of enantiomers. Substituents above and below the ring are drawn with wedges and dashes.



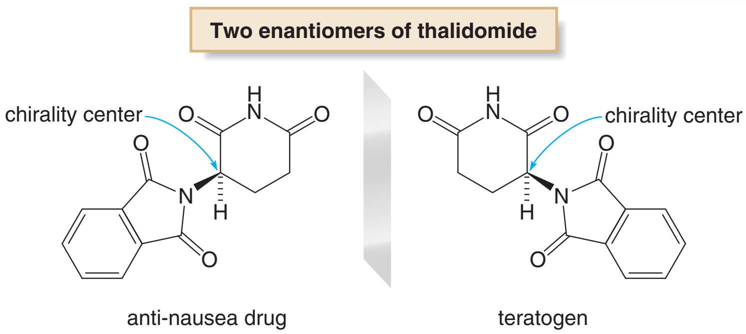
HEALTH NOTE



Although it is a potent teratogen (a substance that causes fetal abnormalities), thalidomide exhibits several beneficial effects, and for this reason, it is now prescribed under strict control for the treatment of Hansen's disease (leprosy). Because it was once thought to be extremely contagious, individuals suffering from Hansen's disease in Hawaii were sent to Kalaupapa, a remote and inaccessible peninsula on the island of Molokai. Hansen's disease is now known to be a treatable bacterial infection completely cured by the sulfa drugs described in Section 13.13.

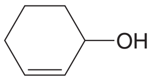
15.4B FOCUS ON HEALTH & MEDICINE THE UNFORGETTABLE LEGACY OF THALIDOMIDE

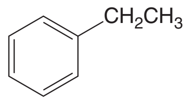
Many biologically active compounds contain one or more chirality centers on ring carbons. For example, **thalidomide,** which contains one such chirality center, was once used as a sedative and anti-nausea drug for pregnant women in Europe and Great Britain from 1959–1962.

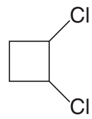


Unfortunately, thalidomide was sold as a mixture of its two enantiomers, and each of these stereoisomers has a different biological activity, a property not uncommon to chiral drugs, as we will see in Section 15.5. While one enantiomer has the desired therapeutic effect, the other enantiomer was responsible for thousands of catastrophic birth defects in children born to women who took the drug during pregnancy. Thalidomide was never approved for use in the United States due to the diligence of Frances Oldham Kelsey, a medical reviewing officer for the Food and Drug Administration, who insisted that the safety data on thalidomide were inadequate.

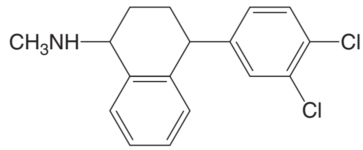
PROBLEM 15.10 Label the chirality centers in each compound. A molecule may have zero, one, or two chirality centers.

a. 

b. 

c. 

PROBLEM 15.11 Label the two chirality centers in sertraline, the generic name for the antidepressant Zoloft.



sertraline

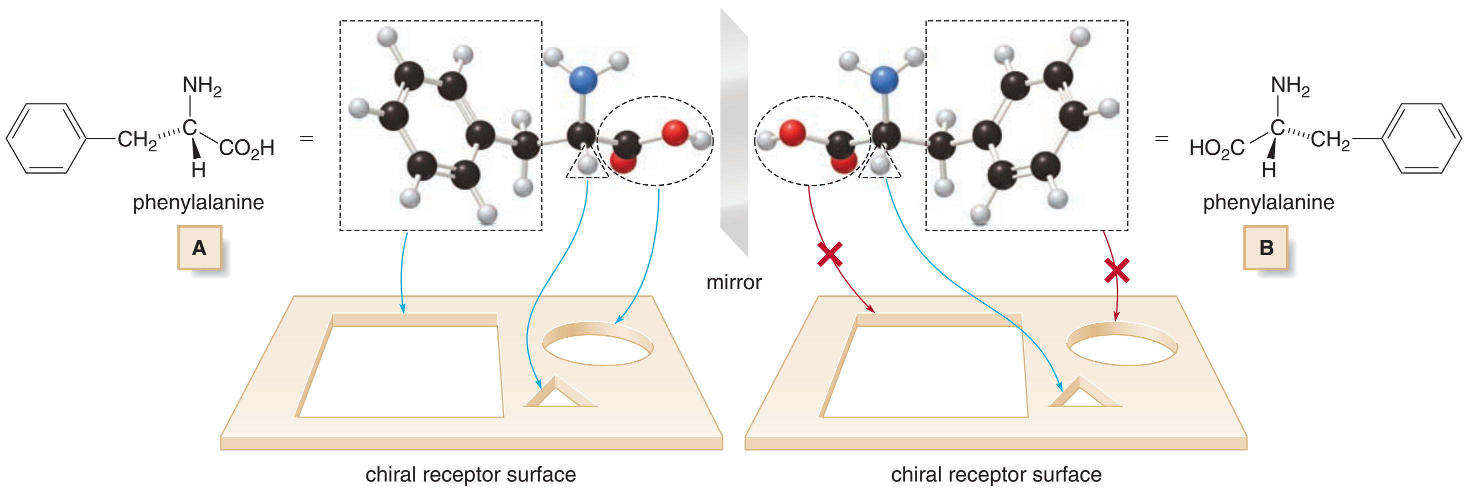
15.5 FOCUS ON HEALTH & MEDICINE CHIRAL DRUGS

A living organism is a sea of chiral molecules. Many drugs are chiral, and often they must interact with a chiral receptor to be effective. One enantiomer of a drug may be effective in treating a disease whereas its mirror image may be ineffective.

Why should such a difference in biological activity be observed? For an everyday analogy, consider what happens when you are given a right-handed glove. A glove is a chiral object, and your right and left hands are also chiral—they are mirror images that are not identical. Only your right hand can fit inside a right glove, not your left. Thus, the glove's utility depends on the hand—it either fits or it doesn't fit.

The same phenomenon is observed with drugs that must interact with a chiral receptor in a cell. One enantiomer "fits" the receptor and evokes a specific response. Its mirror image doesn't fit the same receptor, making it ineffective; or if it "fits" another receptor, it can evoke a totally different response. Figure 15.2 schematically illustrates this difference in binding between two enantiomers and a chiral receptor.

FIGURE 15.2 The Interaction of Two Enantiomers With a Chiral Receptor



One enantiomer of the amino acid phenylalanine, labeled **A,** has three groups that can interact with the appropriate binding sites of the chiral receptor. The groups around the chirality center in the mirror image **B,** however, can never be arranged so that all three groups can bind to these same three binding sites. Thus, enantiomer **B** does not "fit" the same receptor, so it does not evoke the same response.

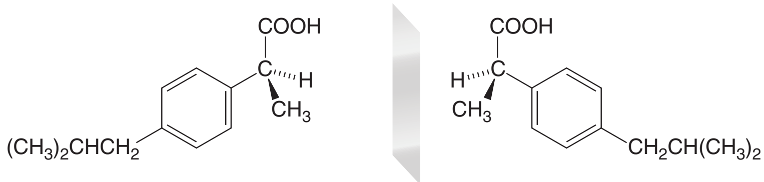
15.5A CHIRAL PAIN RELIEVERS



Ibuprofen is commonly used to relieve headaches, and muscle and joint pain.

Ibuprofen and naproxen are nonsteroidal anti-inflammatory drugs (NSAIDs) that illustrate how two enantiomers can have different biological activities. Both drugs are common over-the-counter remedies that relieve pain and fever, and reduce inflammation.

Ibuprofen is the generic name for the pain relievers known as Motrin and Advil. Ibuprofen has one chirality center, and thus exists as a pair of enantiomers. Only one enantiomer, labeled **A,** is an active anti-inflammatory agent. Its enantiomer **B** is inactive. **B,** however, is slowly converted to **A** in the body. Ibuprofen is sold as a mixture of both enantiomers. **An equal mixture of two enantiomers is called a *racemic mixture*** (pronounced ra-see′-mik).



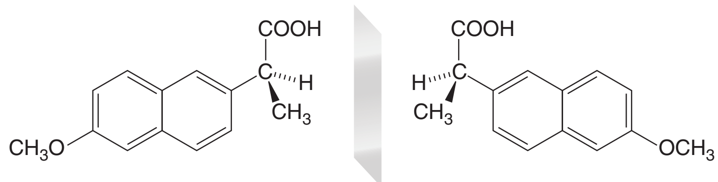
ibuprofen
active anti-inflammatory agent

A

inactive enantiomer

B

One enantiomer of **naproxen,** the pain reliever in Naprosyn and Aleve, is an active anti-inflammatory agent, but its enantiomer is a harmful liver toxin. Changing the orientation of two substituents to form a mirror image can thus alter biological activity to produce an undesirable side effect in the other enantiomer.



naproxen
active anti-inflammatory agent

A

enantiomer
liver toxin

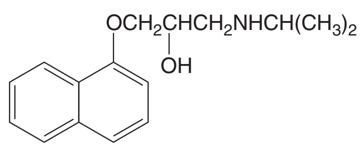
B

These examples illustrate the benefit of marketing a chiral drug as a single active enantiomer. In these instances it should be possible to use smaller doses with fewer side effects, yet many chiral drugs continue to be sold as racemic mixtures, because it is more difficult and therefore more costly to obtain a single enantiomer.

Recent rulings by the Food and Drug Administration have encouraged the development of so-called ***racemic switches,*** the patenting and marketing of a single enantiomer that was originally sold as a racemic mixture. To obtain a new patent on a single enantiomer, however, a company must show evidence that it provides significant benefit over the racemic mixture.

PROBLEM 15.12

Propranolol (trade name: Inderal) is used in the treatment of high blood pressure and heart disease. (a) Locate the chirality center in propranolol. (b) Draw both enantiomers of propranolol. Only one of these enantiomers is biologically active. (c) Draw a diagram similar to Figure 15.2 that illustrates how the two enantiomers of propranolol bind differently to a chiral receptor.



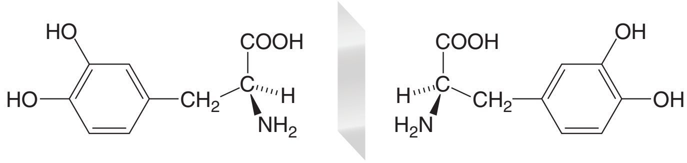
propranolol

15.5B PARKINSON'S DISEASE AND L-DOPA



The broad bean *Vicia faba* produces the drug L-dopa. To meet the large demand for L-dopa today, the commercially available drug is synthesized in the laboratory.

L-Dopa was first isolated from the seeds of the broad bean *Vicia faba,* and since 1967 it has been the drug of choice for the treatment of Parkinson's disease. L-Dopa is a chiral molecule with one chirality center. Unlike ibuprofen, which is still marketed as a racemic mixture, L-dopa, also called levodopa, is sold as a single enantiomer. Like many chiral drugs, only one enantiomer is active against Parkinson's disease. The inactive enantiomer is also responsible for neutropenia, a decrease in certain white blood cells that help to fight infection.



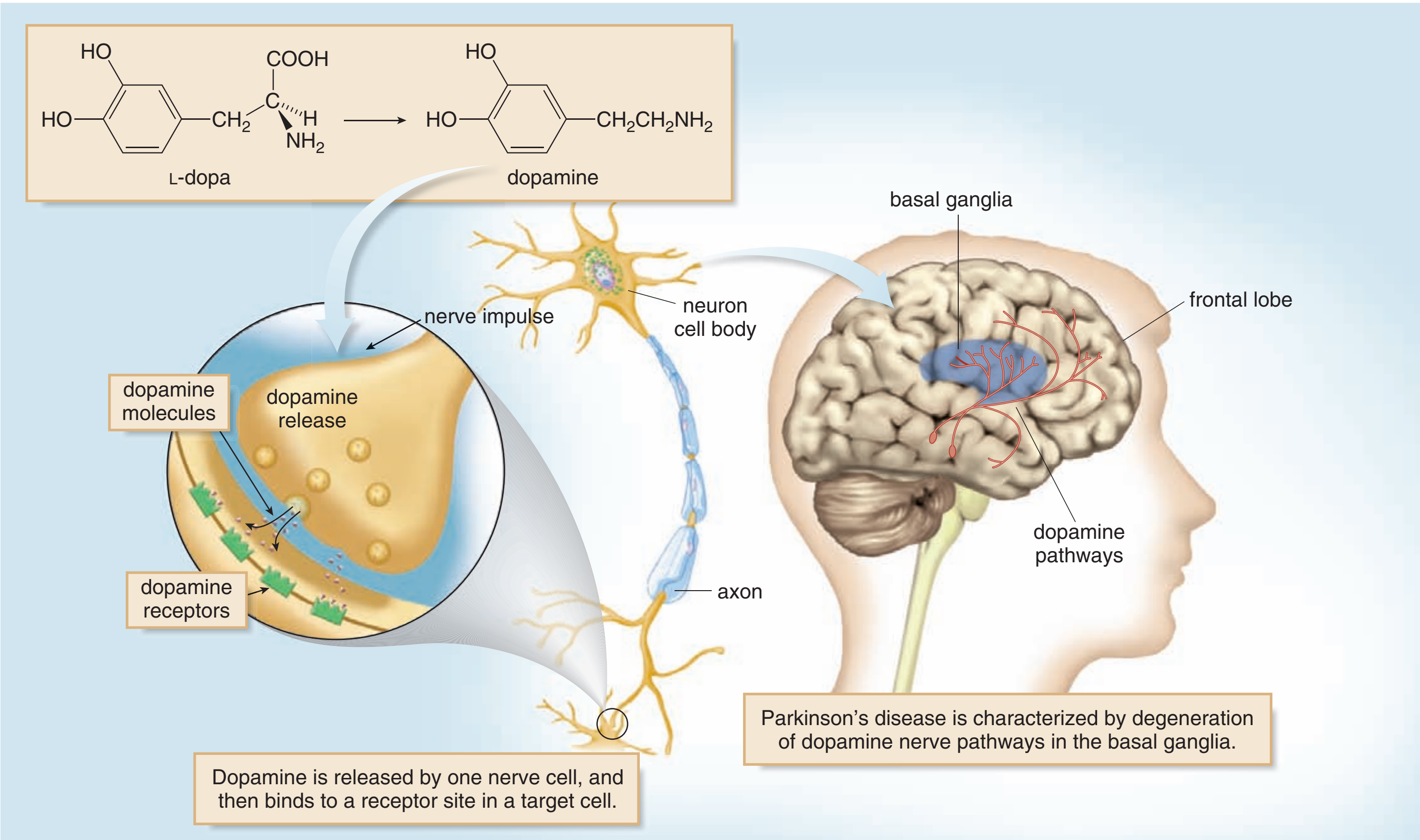
L-dopa
active against Parkinson's disease

D-dopa
enantiomer responsible for undesired side effects

Parkinson's disease, which afflicts 1.5 million individuals in the United States, results from the degeneration of neurons that produce the neurotransmitter dopamine in the brain. Dopamine affects brain processes that control movement and emotions, so proper dopamine levels are needed to maintain an individual's mental and physical health. When the level of dopamine drops, the loss of motor control symptomatic of Parkinson's disease results.

L-Dopa is an oral medication that is transported to the brain by the bloodstream. In the brain it is converted to dopamine (Figure 15.3). Dopamine itself cannot be given as a medication because it cannot pass from the bloodstream into the brain; that is, it does not cross the blood–brain barrier.

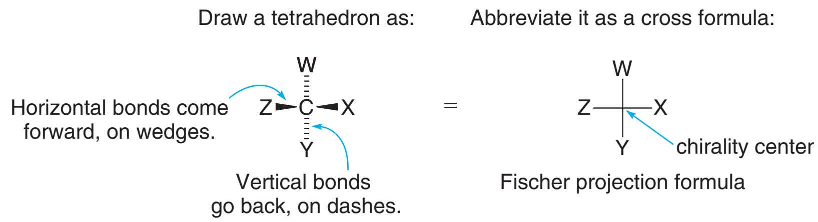
FIGURE 15.3 L-Dopa, Dopamine, and Parkinson's Disease



15.6 FISCHER PROJECTIONS

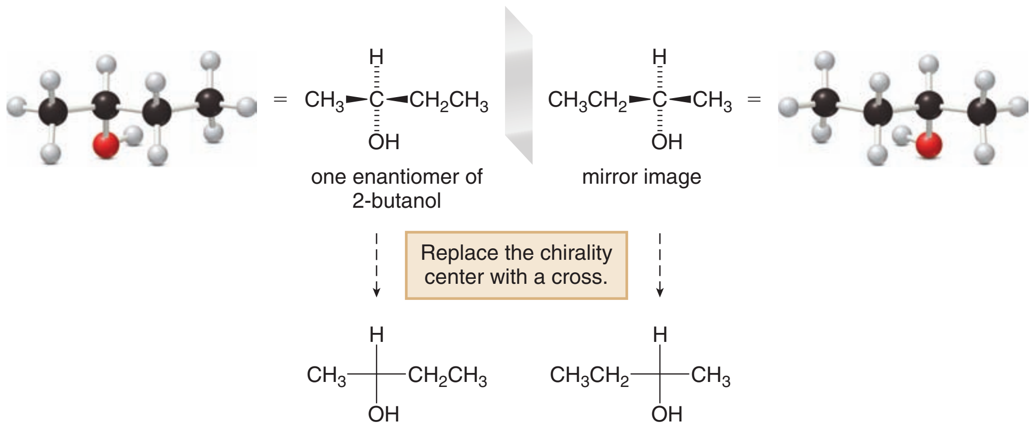
The chirality centers in some organic compounds, most notably carbohydrates (Chapter 20), are often drawn using a different convention than is used for other chirality centers.

Instead of drawing a tetrahedron with two bonds in the plane, one in front of the plane, and one behind it, the **tetrahedron is tipped so that both horizontal bonds come forward (drawn on wedges) and both vertical bonds go behind (on dashed lines).** This structure is then abbreviated by a **cross formula,** also called a **Fischer projection formula.** In a Fischer projection formula, therefore,



- **A carbon atom is located at the intersection of the two lines of the cross.**
- **The horizontal bonds come forward, on wedges.**
- **The vertical bonds go back, on dashed lines.**

For example, to draw the chirality center of 2-butanol [$CH_3CH(OH)CH_2CH_3$, Section 15.3B] using this convention, **draw the tetrahedron with horizontal bonds on wedges and vertical bonds on dashed lines.** Then, **replace the chirality center with a cross** to draw the Fischer projection.

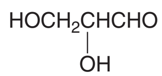


Fischer projection formulas for both enantiomers of 2-butanol

Sample Problem 15.2 illustrates another example of drawing two enantiomers using this convention.

SAMPLE PROBLEM 15.2

Draw both enantiomers of glyceraldehyde, a simple carbohydrate, using Fischer projection formulas.

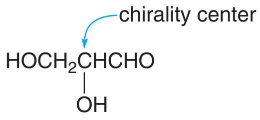


glyceraldehyde

ANALYSIS

- Draw the tetrahedron of one enantiomer with the horizontal bonds on wedges, and the vertical bonds on dashed lines. Arrange the four groups on the chirality center—H, OH, CHO, and CH_2OH—arbitrarily in the first enantiomer.
- Draw the second enantiomer by arranging the substituents in the mirror image so they are a reflection of the groups in the first molecule.
- Replace the chirality center with a cross to draw the Fischer projections.

SOLUTION



glyceraldehyde

Draw the compound. Then, draw the mirror image.



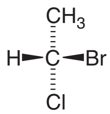
• Horizontal bonds come forward.
• Vertical bonds go back.

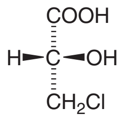


Fischer projection of one enantiomer

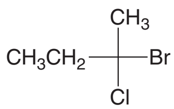
Fischer projection of the second enantiomer

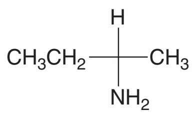
PROBLEM 15.13 Convert each molecule into a Fischer projection formula.

a. 

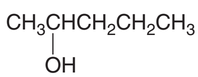
b. 

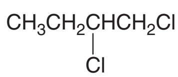
PROBLEM 15.14 Convert each Fischer projection formula into a representation that uses wedges and dashes.

a. 

b. 

PROBLEM 15.15 Draw Fischer projections of both enantiomers for each compound.

a. 

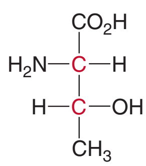
b. 

15.7 COMPOUNDS WITH TWO OR MORE CHIRALITY CENTERS

Although most chiral compounds we have seen thus far have one chirality center, molecules may have two, three, or hundreds of chirality centers. Two examples—tartaric acid and ephedrine—were shown in Section 15.3.

- **A compound with one chirality center has two stereoisomers—a pair of enantiomers.**
- **A compound with two chirality centers has four possible stereoisomers.**

Let's examine the four stereoisomers of the amino acid threonine. The two chirality centers in threonine are labeled in the given structure. Threonine is one of the 20 naturally occurring amino acids needed for protein synthesis. Since humans cannot synthesize threonine, it is an essential amino acid, meaning that it must be obtained in the diet.

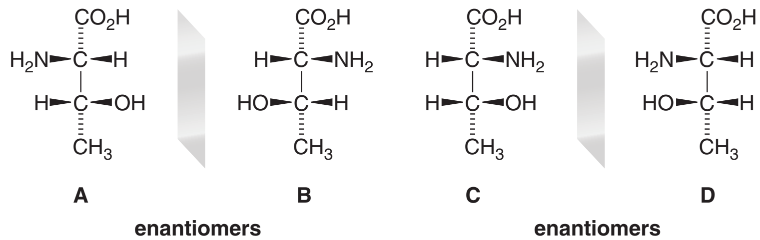


[The chirality centers are labeled in red.]

carbon skeleton of the amino acid threonine

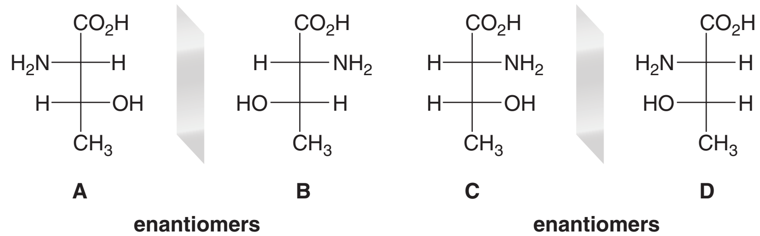
There are four different ways that the groups around two chirality centers can be arranged, shown in structures **A–D.**

The four stereoisomers of a compound with two chirality centers



A and **B** are mirror images, but they are not superimposable, so they are enantiomers. **C** and **D** are also mirror images, but they are not superimposable, so they are enantiomers as well. In other words, with *two* chirality centers, there can be *two* pairs of enantiomers.

Because these structures are drawn with the horizontal bonds of the chirality centers on wedges and the vertical bonds on dashed lines, Fischer projection formulas can be drawn for each stereoisomer by replacing each chirality center by a cross.



Thus, there are four stereoisomers for threonine: enantiomers **A** and **B,** and enantiomers **C** and **D.** What is the relationship between two stereoisomers like **A** and **C?** **A** and **C** are stereoisomers, but if you arrange a mirror plane between **A** and **C** you can see that they are *not* mirror images of each other. **A** and **C** represent a second broad class of stereoisomers, called **diastereomers.**

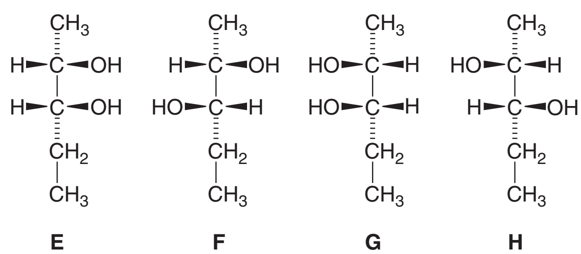
- *Diastereomers* are stereoisomers but they are *not* mirror images of each other.

A and **B** are diastereomers of **C** and **D,** and vice versa. Naturally occurring threonine is a single stereoisomer corresponding to structure **A.** The other stereoisomers do not occur in nature and cannot be used to synthesize biologically active proteins.

SAMPLE PROBLEM 15.3

Considering the four stereoisomers of 2,3-pentanediol (**E–H**): (a) Which compound is an enantiomer of **E?** (b) Which compound is an enantiomer of **F?** (c) What two compounds are diastereomers of **G?**

Four stereoisomers of 2,3-pentanediol:



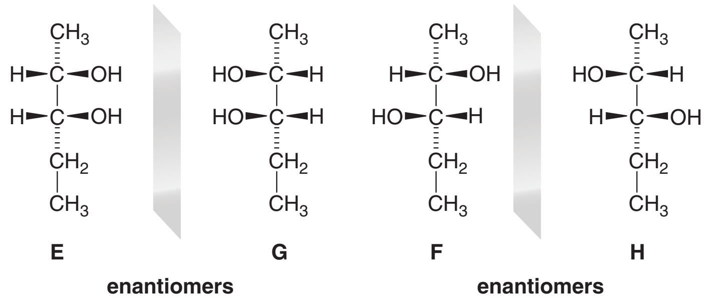
ANALYSIS Keep in mind the definitions:

- **Enantiomers are stereoisomers that are nonsuperimposable mirror images of each other.** Look for two compounds that when placed side-by-side have the groups on both chirality centers drawn as a *reflection* of each other. A given compound has only one possible enantiomer.
- **Diastereomers are stereoisomers that are *not* mirror images of each other.**

SOLUTION

a. **E** and **G** are enantiomers because they are mirror images that do not superimpose on each other.

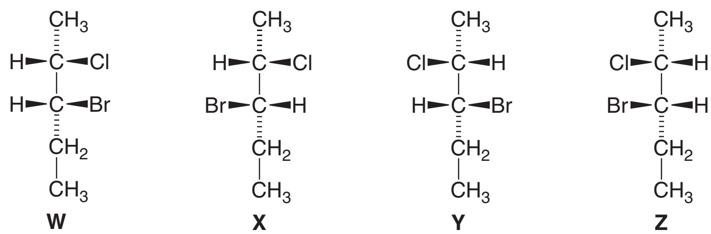
b. **F** and **H** are enantiomers for the same reason.



c. Any compound that is a stereoisomer of **G** but is not its mirror image is a diastereomer. Thus, **F** and **H** are diastereomers of **G.**

PROBLEM 15.16 Answer the following questions about the four stereoisomers of 3-bromo-2-chloropentane (**W–Z**). (a) Which compound is the enantiomer of **W?** (b) Which compound is the enantiomer of **X?** (c) What two compounds are diastereomers of **Y?** (d) What two compounds are diastereomers of **Z?**

Four stereoisomers of 3-bromo-2-chloropentane:



PROBLEM 15.17 Convert each stereoisomer (**W–Z**) in Problem 15.16 into a Fischer projection.

15.8 FOCUS ON THE HUMAN BODY THE SENSE OF SMELL

Research suggests that the odor of a particular molecule is determined more by its shape than by the presence of a particular functional group (Figure 15.4). For example, hexachloroethane (Cl_3CCCl_3) and cyclooctane have no obvious structural similarities. However, both molecules have a camphor-like odor, a fact attributed to their similar spherical shape, which is readily shown using space-filling models.

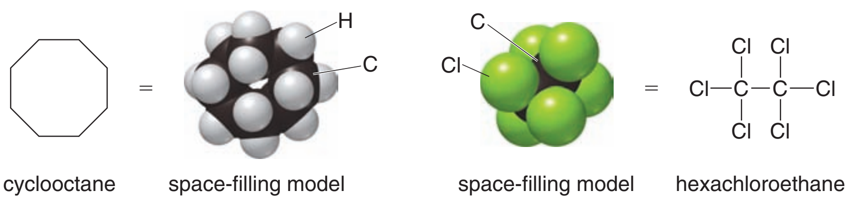
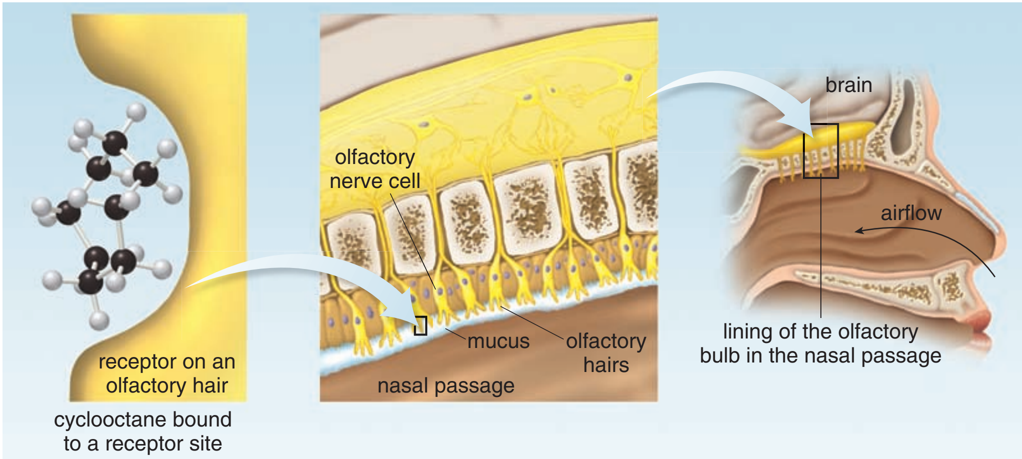
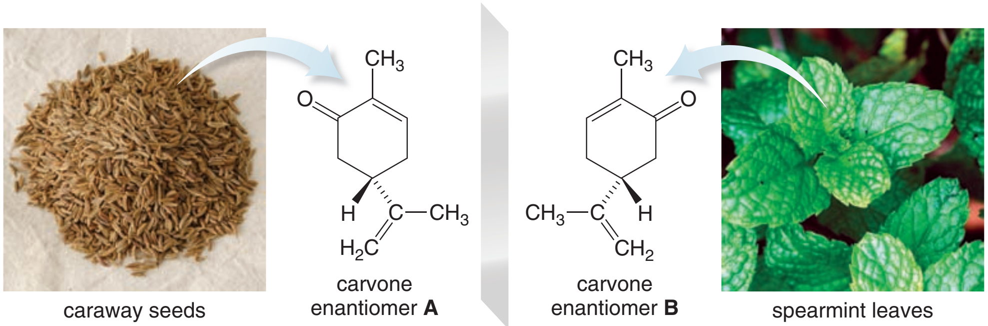


FIGURE 15.4 The Shape of Molecules and the Sense of Smell



Cyclooctane and other molecules similar in shape bind to a particular olfactory receptor on the nerve cells that lie at the top of the nasal passage. Binding results in a nerve impulse that travels to the brain, which interprets impulses from particular receptors as specific odors.

Since enantiomers interact with chiral smell receptors, some enantiomers have different odors. There are a few well-characterized examples of this phenomenon in nature. For example, one enantiomer of carvone is responsible for the odor of caraway, whereas the other carvone enantiomer is responsible for the odor of spearmint.



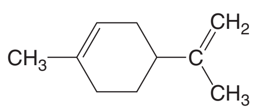
A has the odor of caraway.

B has the odor of spearmint.

Thus, the three-dimensional structure of a molecule is important in determining its odor.

PROBLEM 15.18

Limonene is similar to carvone in that each enantiomer has a different odor; one enantiomer occurs in lemons and the other occurs in oranges. Identify the chirality center in limonene and draw both enantiomers of limonene.



limonene

CHAPTER HIGHLIGHTS

KEY TERMS

Achiral (15.2)
Chiral (15.2)
Chirality center (15.2)
Constitutional isomer (15.1)
Cross formula (15.6)
Diastereomer (15.7)
Enantiomer (15.2)
Fischer projection formula (15.6)
Racemic mixture (15.5)
Stereochemistry (15.1)
Stereoisomer (15.1)

KEY CONCEPTS

1 When is a molecule chiral or achiral? (15.2)

- A chiral molecule is not superimposable on its mirror image.
- An achiral molecule is superimposable on its mirror image.
- To see whether a molecule is chiral, draw it and its mirror image and see if all of the atoms and bonds align.

2 What is a chirality center? (15.2, 15.3)

- A chirality center is a carbon with four different groups around it.
- A molecule with one chirality center is chiral.

3 What are enantiomers? (15.2, 15.3)

- Enantiomers are mirror images that are not superimposable on each other. To draw two enantiomers, draw one molecule in three dimensions around the chirality center. Then draw the mirror image so that the substituents are a reflection of the groups in the first molecule.

4 Why do some chiral drugs have different properties from their mirror-image isomers? (15.5)

- When a chiral drug must interact with a chiral receptor, only one enantiomer fits the receptor properly and evokes a specific response. Ibuprofen, naproxen, and L-dopa are examples of chiral drugs in which the two enantiomers have very different properties.

5 What is a Fischer projection? (15.6)

- A Fischer projection is a specific way of depicting a chirality center. The chirality center is located at the intersection of a cross. The horizontal lines represent bonds that come out of the plane on wedges, and the vertical lines represent bonds that go back on dashed lines.

6 What is the difference between an enantiomer and a diastereomer? (15.7)

- Enantiomers are stereoisomers that are nonsuperimposable mirror images of each other.
- Diastereomers are stereoisomers that are *not* mirror images of each other.

7 How is the shape of a molecule related to its odor? (15.8)

- It is thought that the odor of a molecule is determined more by its shape than the presence of a particular functional group, so compounds of similar shape have similar odors. For an odor to be perceived, a molecule must bind to an olfactory receptor, resulting in a nerve impulse that travels to the brain. Enantiomers may have different odors because they bind with chiral receptors and each enantiomer fits the chiral receptors in a different way.

PROBLEMS

Selected in-chapter and end-of-chapter problems have brief answers provided in Appendix B.

Chiral Compounds, Chirality Centers, and Enantiomers

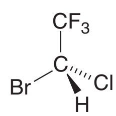
15.19 Label each of the following objects as chiral or achiral: (a) chalk; (b) shoe; (c) baseball glove; (d) soccer ball.

15.20 Label each of the following objects as chiral or achiral: (a) boot; (b) index card; (c) scissors; (d) drinking glass.

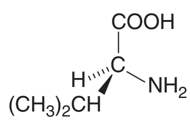
15.21 Explain the following statement. Butane ($CH_3CH_2CH_2CH_3$) has a mirror image but it does not have an enantiomer.

15.22 Explain why the human body is chiral.

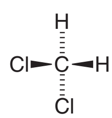
15.23 Draw a mirror image for each compound. Label each compound as chiral or achiral.

a. 

halothane
(general anesthetic)

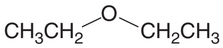
b. 

valine
(naturally occurring amino acid)

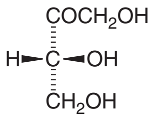
c. 

dichloromethane
(common solvent)

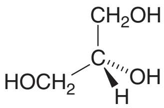
15.24 Draw a mirror image for each compound. Label each compound as chiral or achiral.

a. 

diethyl ether
(general anesthetic)

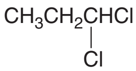
b. 

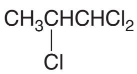
erythrulose
(a carbohydrate)

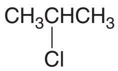
c. 

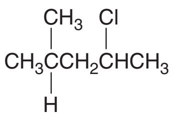
glycerol
(triol used in lotions)

15.25 Label the chirality center (if one exists) in each compound. Compounds contain zero or one chirality center.

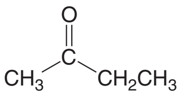
a. 

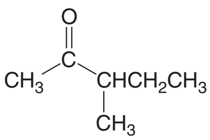
b. 

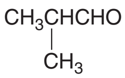
c. 

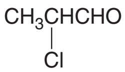
d. 

15.26 Label the chirality center (if one exists) in each compound. Compounds contain zero or one chirality center.

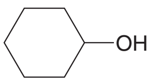
a. 

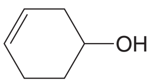
b. 

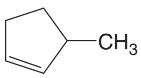
c. 

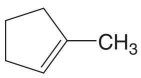
d. 

15.27 Label the chirality center (if one exists) in each cyclic compound. Some compounds contain no chirality centers.

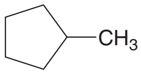
a. 

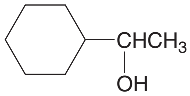
b. 

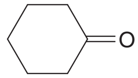
c. 

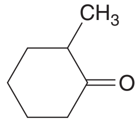
d. 

15.28 Label the chirality center (if one exists) in each cyclic compound. Some compounds contain no chirality centers.

a. 

b. 

c. 

d. 

15.29 Draw the structure of a compound that fits each description:

a. an alkane of molecular formula C_7H_{16} that contains one chirality center
b. an alcohol of molecular formula $C_6H_{14}O$ that contains one chirality center

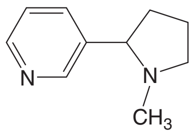
15.30 Draw the structure of a compound that fits each description:

a. an alkyl bromide of molecular formula C_4H_9Br that contains one chirality center
b. a diol of molecular formula $C_5H_{12}O_2$ that contains two chirality centers

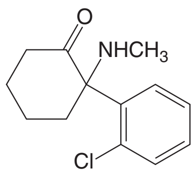
15.31 Explain why a carbonyl carbon can never be a chirality center.

15.32 Explain why a carbon atom that is part of a triple bond can never be a chirality center.

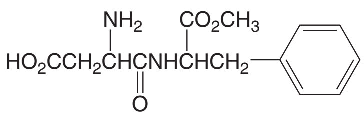
15.33 Locate the chirality center(s) in each biologically active compound.

a. 

nicotine
(addictive stimulant from tobacco)

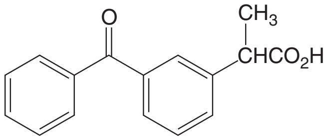
b. 

ketamine
(anesthetic)

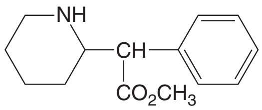
c. 

aspartame
Trade name: Equal
(synthetic sweetener)

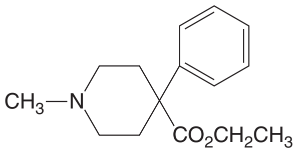
15.34 Locate the chirality center(s) in each drug.

a. 

ketoprofen
(anti-inflammatory agent)

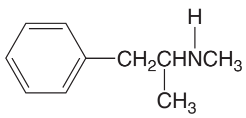
b. 

methylphenidate
Trade name: Ritalin
(used for attention deficit hyperactivity disorder)

c. 

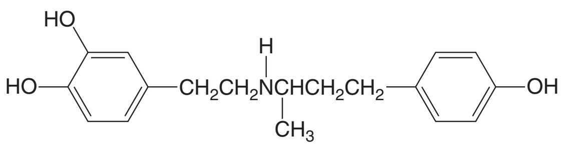
meperidine
Trade name: Demerol
(narcotic pain reliever)

15.35 Methamphetamine is an addictive stimulant sold illegally as "speed," "meth," or "crystal meth." Identify the chirality center in methamphetamine, and then draw both enantiomers in three dimensions around the chirality center.



methamphetamine

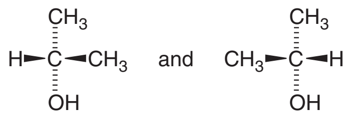
15.36 Dobutamine is a heart stimulant used in stress tests to measure cardiac fitness. Identify the chirality center in dobutamine, and then draw both enantiomers in three dimensions around the chirality center.

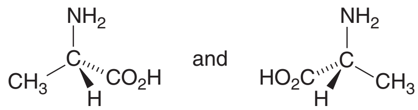


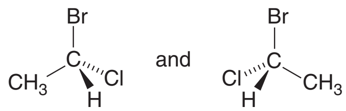
dobutamine

Isomers

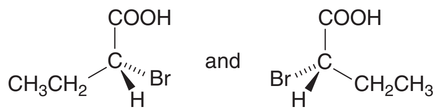
15.37 How are the compounds in each pair related? Are they identical molecules or enantiomers?

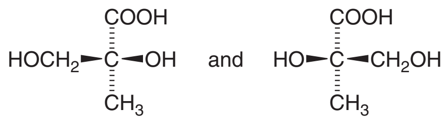
a. 

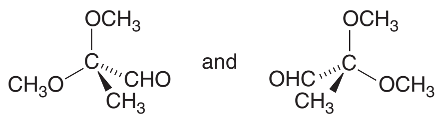
b. 

c. 

15.38 How are the compounds in each pair related? Are they identical molecules or enantiomers?

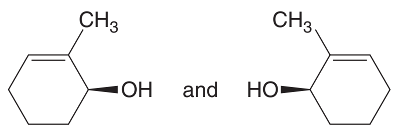
a. 

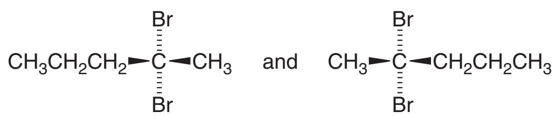
b. 

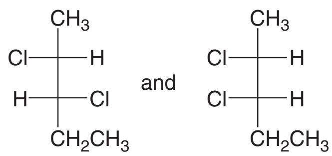
c. 

15.39 How are the molecules in each pair related? Choose from: identical molecules, constitutional isomers, enantiomers, diastereomers, or not isomers of each other.

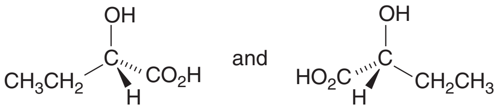
a. $CH_3CH_2CH_2OCH_3$ and $CH_3CH_2OCH_2CH_3$

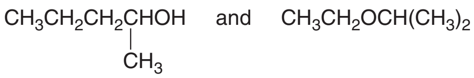
b. 

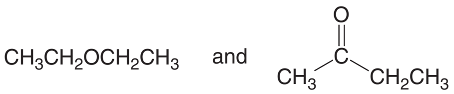
c. 

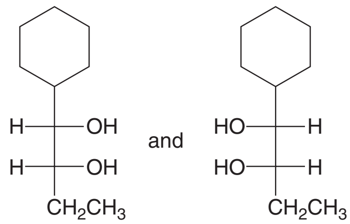
d. 

15.40 How are the molecules in each pair related? Choose from: identical molecules, constitutional isomers, enantiomers, diastereomers, or not isomers of each other.

a. 

b. 

c. 

d. 

15.41 Answer each question with a compound of molecular formula $C_5H_{10}O_2$.

a. Draw the structure of a compound that contains a COOH group and one chirality center.

b. Draw the structure of a carboxylic acid that is a constitutional isomer of the compound drawn in part (a).

c. Draw the structure of a constitutional isomer of the compound drawn in part (a), which contains a different functional group.

15.42 Answer each question with a compound of molecular formula $C_5H_{12}O$.

a. Draw the structure of a compound that contains an ether group and one chirality center.

b. Draw the structure of an ether that is a constitutional isomer of the compound drawn in part (a).

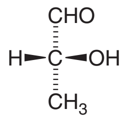
c. Draw the structure of a constitutional isomer of the compound drawn in part (a), which contains a different functional group.

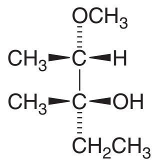
15.43 Draw the structure of the four constitutional isomers of molecular formula $C_5H_{10}O$ that contain an aldehyde (—CHO) as a functional group. Label any chirality center present in each compound. Some compounds have no chirality centers.

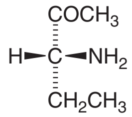
15.44 Although there are four constitutional isomers of molecular formula C_4H_9Cl, only one contains a chirality center and can therefore exist as a pair of enantiomers. Draw both enantiomers of this alkyl chloride in three dimensions around the chirality center.

Fischer Projections

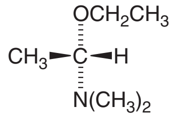
15.45 Convert each three-dimensional representation into a Fischer projection.

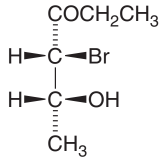
a. 

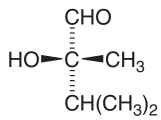
c. 

b. 

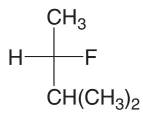
15.46 Convert each three-dimensional representation into a Fischer projection.

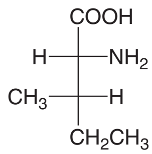
a. 

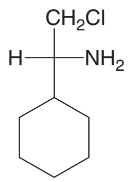
c. 

b. 

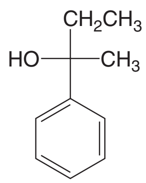
15.47 Convert each Fischer projection into a three-dimensional representation with wedges and dashed bonds.

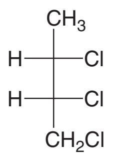
a. 

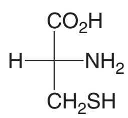
c. 

b. 

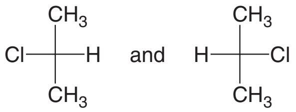
15.48 Convert each Fischer projection into a three-dimensional representation with wedges and dashed bonds.

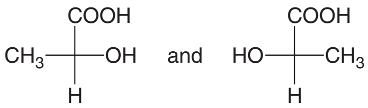
a. 

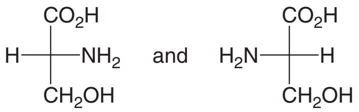
c. 

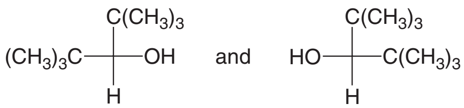
b. 

15.49 How are the Fischer projection formulas in each pair related to each other? Are they identical or are they enantiomers?

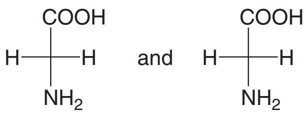
a. 

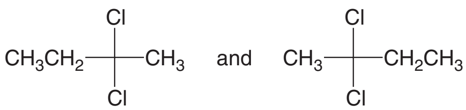
b. 

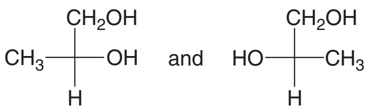
c. 

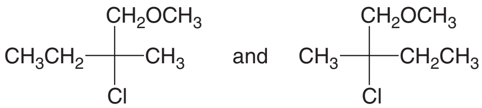
d. 

15.50 How are the Fischer projection formulas in each pair related to each other? Are they identical or are they enantiomers?

a. 

b. 

c. 

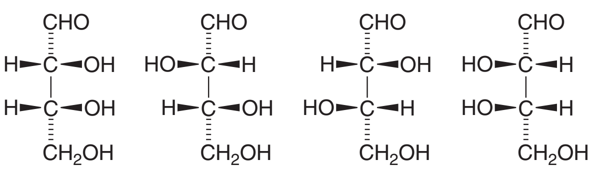
d. 

Enantiomers and Diastereomers

15.51 In what way are two enantiomers different from two diastereomers?

15.52 What are the two major types of stereoisomers? Give an example of each type.

15.53 Consider the stereoisomers **(A–D)** drawn below. These compounds are four-carbon sugars, as we will learn in Chapter 20.

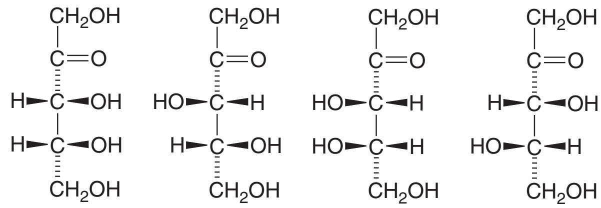


A **B** **C** **D**

a. How are the compounds in each pair related? Are the compounds enantiomers or diastereomers: [1] **A** and **B;** [2] **A** and **C;** [3] **A** and **D;** [4] **B** and **C;** [5] **B** and **D;** [6] **C** and **D?**

b. Draw a constitutional isomer of **A** that contains a ketone, not an aldehyde.

15.54 Consider the stereoisomers **(E–H)** drawn below. These compounds are five-carbon sugars, as we will learn in Chapter 20.



E **F** **G** **H**

a. How are the compounds in each pair related? Are the compounds enantiomers or diastereomers: [1] **E** and **F;** [2] **E** and **G;** [3] **E** and **H;** [4] **F** and **G;** [5] **F** and **H;** [6] **G** and **H?**

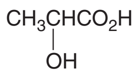
b. Draw a constitutional isomer of **E** that contains an aldehyde, not a ketone.

15.55 In Chapter 13 we learned that cis and trans alkenes are stereoisomers. Are *cis*-2-butene and *trans*-2-butene enantiomers or diastereomers? Explain your choice.

15.56 Are *cis*-2-butene and *trans*-2-butene chiral or achiral compounds? Explain your choice.

Applications

15.57 Lactic acid is a product of glucose metabolism. During periods of strenuous exercise, lactic acid forms faster than it can be oxidized, resulting in the aching feeling of tired muscles.



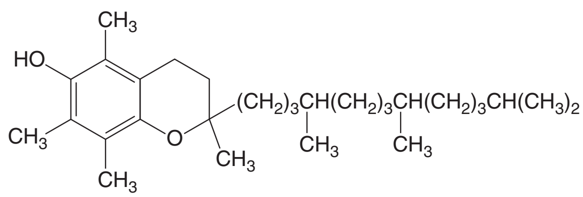
lactic acid

a. Locate the chirality center in lactic acid.

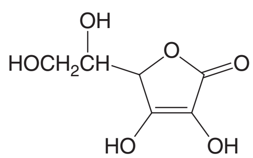
b. Draw both enantiomers of lactic acid in three dimensions around the chirality center.

c. Draw Fischer projection formulas for both enantiomers of lactic acid.

15.58 Locate the chirality centers in each vitamin.

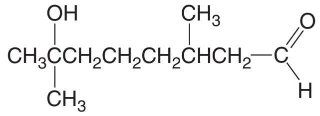
a. 

vitamin E

b. 

vitamin C

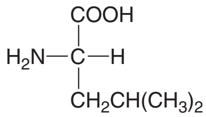
15.59 Hydroxydihydrocitronellal is another example of a compound that has two enantiomers that smell differently. One enantiomer smells minty, and the other smells like lily of the valley.



hydroxydihydrocitronellal

a. Locate the chirality center in this compound.
b. Draw both enantiomers in three dimensions around the chirality center.
c. Draw Fischer projection formulas for both enantiomers.

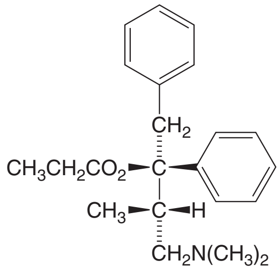
15.60 Two enantiomers can sometimes taste very differently. L-Leucine, a naturally occurring amino acid used in protein synthesis, tastes bitter, but its enantiomer, D-leucine, tastes sweet.



leucine

a. Locate the chirality center in leucine.
b. Draw both enantiomers in three dimensions around the chirality center.
c. Draw Fischer projection formulas for both enantiomers.

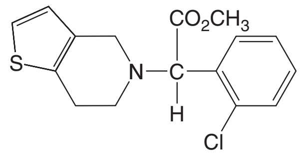
15.61 Answer the following questions about the analgesic propoxyphene (trade name: Darvon).



Darvon

a. Label the chirality centers.
b. Draw the enantiomer. Like many of the drugs discussed in Section 15.5, the enantiomer, levopropoxyphene (trade name: Novrad) has different biological properties. Levopropoxyphene is an antitussive agent, meaning it relieves coughs. (Do you notice anything about the trade names Darvon and Novrad?)
c. Draw the structure of one diastereomer.
d. Draw the structure of one constitutional isomer.
e. Convert Darvon to a Fischer projection formula.

15.62 Plavix, the trade name for the generic drug clopidogrel, is used in the treatment of coronary artery disease. Like many newer drugs, Plavix is sold as a single enantiomer.

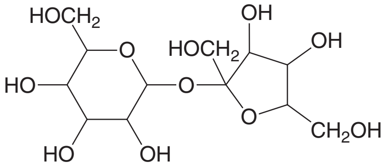


clopidogrel
Trade name: Plavix

a. Locate the chirality center.
b. Draw both enantiomers in three dimensions around the chirality center.
c. Convert both enantiomers to Fischer projection formulas.

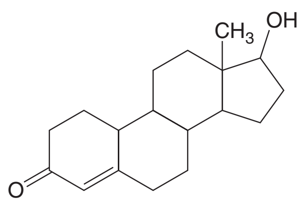
CHALLENGE QUESTIONS

15.63 Identify the nine chirality centers in sucrose, the sweet-tasting carbohydrate we use as table sugar.



sucrose

15.64 Identify the six chirality centers in the anabolic steroid nandrolone. Nandrolone is used to increase muscle mass in body builders and athletes, although it is not permitted in competitive sports.



nandrolone

16

CHAPTER OUTLINE

CHAPTER GOALS

In this chapter you will learn how to:

1. Identify the characteristics of aldehydes and ketones
2. Name aldehydes and ketones
3. Give examples of useful aldehydes and ketones
4. Draw the products of oxidation reactions of aldehydes
5. Draw the products of reduction reactions of aldehydes and ketones
6. Understand the basic reactions involved in vision
7. Identify and prepare hemiacetals and acetals



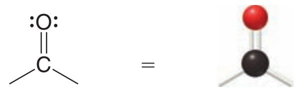
11-*cis*-Retinal is the light-sensitive aldehyde that plays a key role in the chemistry of vision for all vertebrates, arthropods, and mollusks.

ALDEHYDES AND KETONES

CHAPTER 16 is the first of two chapters that concentrate on compounds that contain a **carbonyl group (C═O),** perhaps the most important functional group in organic chemistry. In this chapter we examine **aldehydes** and **ketones,** compounds that contain a carbonyl carbon bonded to hydrogen or carbon atoms. Aldehydes and ketones occur widely in nature, and also serve as useful starting materials and solvents in industrial processes. All simple carbohydrates contain a carbonyl group, and more complex carbohydrates are derived from reactions discussed in this chapter.

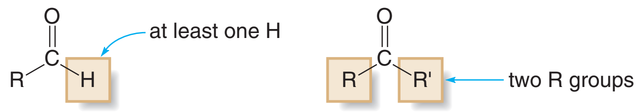
16.1 STRUCTURE AND BONDING

Two broad classes of compounds contain a ***carbonyl group.***



carbonyl group

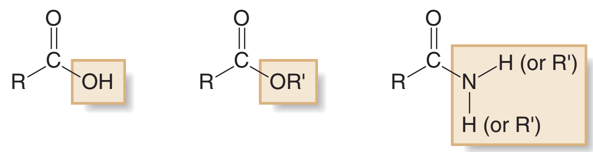
1. Compounds that have only carbon and hydrogen atoms bonded to the carbonyl group



aldehyde ketone

- **An *aldehyde* has at least one H atom bonded to the carbonyl group.**
- **A *ketone* has two alkyl groups bonded to the carbonyl group.**

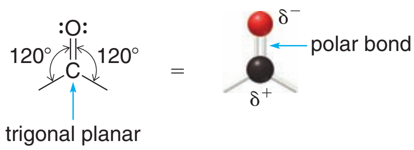
2. Compounds that contain an electronegative atom bonded to the carbonyl group



carboxylic acid ester amide

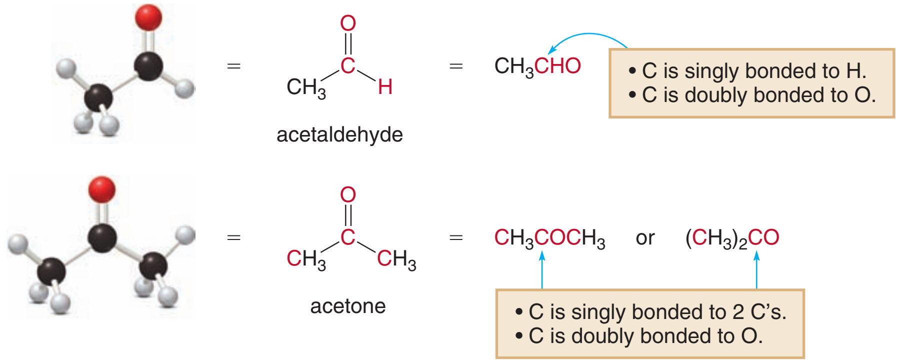
These compounds include **carboxylic acids, esters,** and **amides,** which contain an electronegative oxygen or nitrogen atom bonded directly to the carbonyl carbon. Esters and amides are called **carboxylic acid derivatives,** since they can be prepared from carboxylic acids. Carboxylic acids and their derivatives are discussed in Chapter 17, while aldehydes and ketones are the subject of this chapter.

Two structural features dominate the properties and chemistry of the carbonyl group.

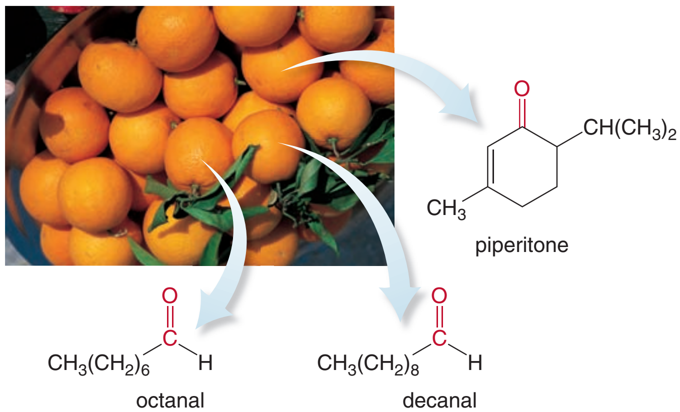


- **The carbonyl carbon atom is trigonal planar, and all bond angles are 120°. In this way the carbonyl carbon resembles the carbons of a carbon–carbon double bond.**
- **Since oxygen is more electronegative than carbon, a carbonyl group is polar. The carbonyl carbon is electron poor (δ^+) and the oxygen is electron rich (δ^-). In this way the carbonyl carbon is very different from the carbons of a nonpolar carbon–carbon double bond.**

As mentioned in Chapter 11, the double bond of a carbonyl group is usually omitted in drawing shorthand structures. An aldehyde is often written as **RCHO.** Remember that the **H atom is bonded to the carbon atom,** not the oxygen. Likewise, a ketone is written as **RCOR,** or if both alkyl groups are the same, **R_2CO.**



Many simple aldehydes and ketones are naturally occurring. For example, octanal, decanal, and piperitone are among the 70 organic compounds that contribute to the flavor and odor of an orange.

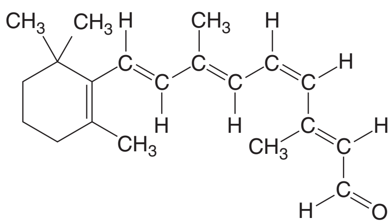


PROBLEM 16.1 Draw out each compound to clearly show what groups are bonded to the carbonyl carbon. Label each compound as a ketone or aldehyde.

a. CH_3CH_2CHO b. $CH_3CH_2COCH_3$ c. $(CH_3)_3CCOCH_3$ d. $(CH_3CH_2)_2CHCHO$

PROBLEM 16.2 Draw the structure of the three constitutional isomers of molecular formula C_4H_8O that contain a carbonyl group. Label each compound as a ketone or aldehyde.

PROBLEM 16.3 Label each trigonal planar carbon in 11-*cis*-retinal, the chapter-opening molecule whose chemistry is discussed in Section 16.6.



11-*cis*-retinal

16.2 NOMENCLATURE

Both IUPAC and common names are used for aldehydes and ketones.

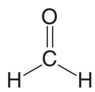
16.2A NAMING ALDEHYDES

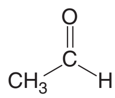
- **In IUPAC nomenclature, aldehydes are identified by the suffix *-al*.**

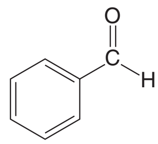
To name an aldehyde using the IUPAC system:

1. **Find the longest chain containing the CHO group, and change the *-e* ending of the parent alkane to the suffix *-al*.**
2. **Number the chain or ring to put the CHO group at C1, but omit this number from the name. Apply all of the other usual rules of nomenclature.**

Simple aldehydes have common names that are widely used. In fact, the common names **formaldehyde, acetaldehyde,** and **benzaldehyde** are virtually always used instead of their IUPAC names. Common names all contain the suffix ***-aldehyde.***


formaldehyde (methanal)

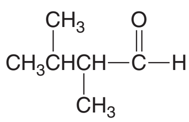

acetaldehyde (ethanal)

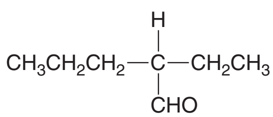

benzaldehyde (benzenecarbaldehyde)

(IUPAC names are in parentheses.)

SAMPLE PROBLEM 16.1

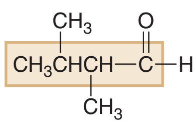
Give the IUPAC name for each aldehyde.

a. 

b. 

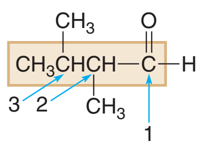
ANALYSIS AND SOLUTION

a. [1] Find and name the longest chain containing the CHO.



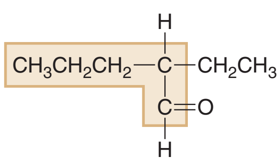
butane ---→ butan*al*
(4 C's)

[2] Number and name substituents, making sure the CHO group is at C1.



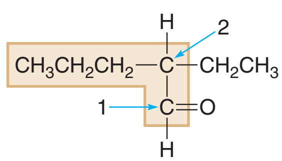
Answer: 2,3-dimethylbutanal

b. [1] Find and name the longest chain containing the CHO.



pentane ---→ pentan*al*
(5 C's)

[2] Number and name substituents, making sure the CHO group is at C1.

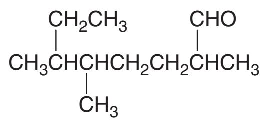


Answer: 2-ethylpentanal

PROBLEM 16.4 Give the IUPAC name for each aldehyde.

a. $(CH_3)_2CHCH_2CH_2CH_2CHO$

b. $(CH_3)_3CC(CH_3)_2CH_2CHO$

c. 

PROBLEM 16.5 Give the structure corresponding to each IUPAC name.

a. 2-chloropropanal
b. 3,4,5-triethylheptanal
c. 3,6-diethylnonanal
d. *o*-ethylbenzaldehyde

16.2B NAMING KETONES

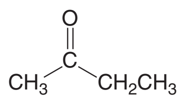
- **In the IUPAC system, ketones are identified by the suffix *-one.***

To name an acyclic ketone using IUPAC rules:

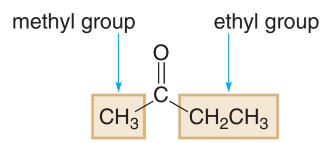
1. **Find the longest chain containing the carbonyl group, and change the *-e* ending of the parent alkane to the suffix *-one.***
2. **Number the carbon chain to give the carbonyl carbon the lower number. Apply all of the other usual rules of nomenclature.**

With cyclic ketones, numbering always begins at the carbonyl carbon, but the “1” is usually omitted from the name. The ring is then numbered clockwise or counterclockwise to give the first substituent the lower number.

Most common names for ketones are formed by **naming both alkyl groups** on the carbonyl carbon, **arranging them alphabetically,** and adding the word ***ketone.*** Using this method, the common name for 2-butanone becomes ethyl methyl ketone.

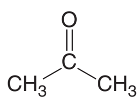


IUPAC name: **2-butanone**

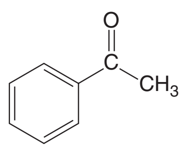


Common name: **ethyl methyl ketone**

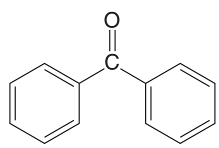
Three widely used common names for some simple ketones do not follow this convention:



acetone

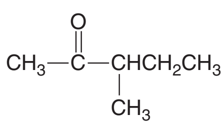


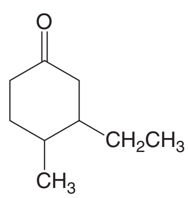
acetophenone



benzophenone

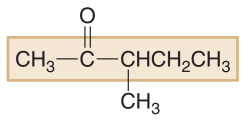
SAMPLE PROBLEM 16.2 Give IUPAC names for each ketone.

a. 

b. 

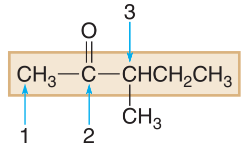
ANALYSIS AND SOLUTION

a. [1] Find and name the longest chain containing the carbonyl group.



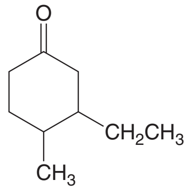
pentane ----→ pentan*one*
(5 C's)

[2] Number and name substituents, making sure the carbonyl carbon has the lowest possible number.



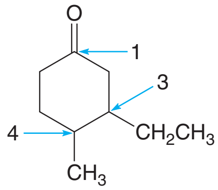
Answer: 3-methyl-2-pentanone

b. [1] Name the ring.



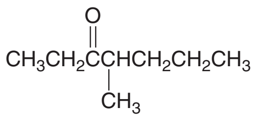
cyclohexane ----→ cyclohexan*one*
(6 C's)

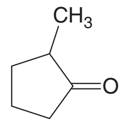
[2] Number and name substituents, making sure the carbonyl carbon is at C1.

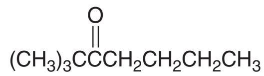


Answer: 3-ethyl-4-methylcyclohexanone

PROBLEM 16.6 Give the IUPAC name for each ketone.

a. 

b. 

c. 

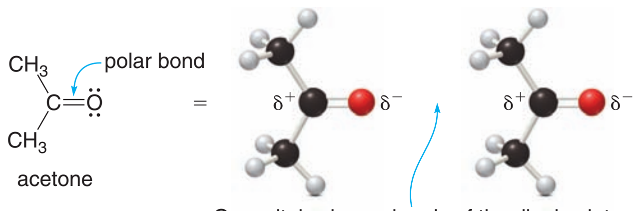
PROBLEM 16.7 Draw the structure of 2-octanone, a ketone partly responsible for the flavor of some mushrooms.

PROBLEM 16.8 Give the structure corresponding to each name.

a. butyl ethyl ketone
b. 2-methyl-3-pentanone
c. *p*-ethylacetophenone
d. 2-propylcyclobutanone

16.3 PHYSICAL PROPERTIES

Because aldehydes and ketones have a polar carbonyl group, they are **polar molecules** with stronger intermolecular forces than the hydrocarbons of Chapters 12 and 13. Since they have no O—H bond, two molecules of RCHO or RCOR are incapable of intermolecular hydrogen bonding, giving them weaker intermolecular forces than alcohols.



Oppositely charged ends of the dipoles interact.

As a result:

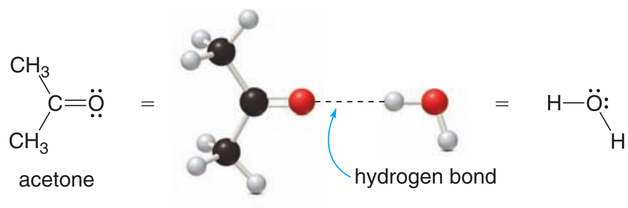
- **Aldehydes and ketones have *higher* boiling points than hydrocarbons of comparable size.**
- **Aldehydes and ketones have *lower* boiling points than alcohols of comparable size.**

$CH_3CH_2CH_2CH_2CH_3$	$CH_3CH_2CH_2CHO$	$CH_3CH_2CH_2CH_2OH$
pentane	butanal	1-butanol
bp 36 °C	bp 76 °C	bp 118 °C
	$CH_3CH_2COCH_3$	
	2-butanone	
	bp 80 °C	

→

Increasing strength of intermolecular forces
Increasing boiling point

Based on the general rule governing solubility (i.e., **"like dissolves like,"** Section 8.2), aldehydes and ketones are soluble in organic solvents. Moreover, because aldehydes and ketones contain an oxygen atom with an available lone pair, they can intermolecularly hydrogen bond to water.

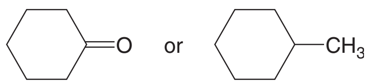


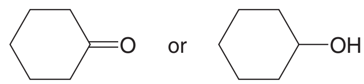
As a result:

- **Low molecular weight aldehydes and ketones (those having less than six carbons) are soluble in both organic solvents and water.**
- **Higher molecular weight aldehydes and ketones (those having six carbons or more) are soluble in organic solvents, but insoluble in water.**

PROBLEM 16.9

Which compound in each pair has the higher boiling point?

a. 

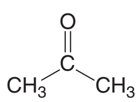
c. 

b. $(CH_3CH_2)_2CO$ or $(CH_3CH_2)_2C{=}CH_2$

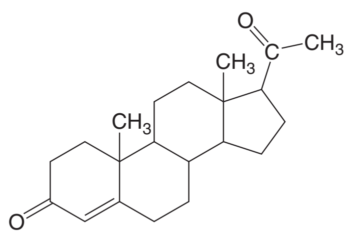
d. $CH_3(CH_2)_6CH_3$ or $CH_3(CH_2)_5CHO$

PROBLEM 16.10

Acetone and progesterone are two ketones that occur naturally in the human body. Discuss the solubility properties of both compounds in water and organic solvents.



acetone

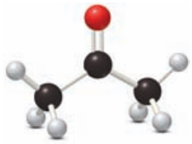


progesterone

16.4 FOCUS ON HEALTH & MEDICINE INTERESTING ALDEHYDES AND KETONES



formaldehyde
$CH_2{=}O$



acetone
$(CH_3)_2C{=}O$

Formaldehyde ($CH_2{=}O$, the simplest aldehyde) is a starting material for the synthesis of many resins and plastics, and billions of pounds are produced annually in the United States. Formaldehyde is also sold as a 37% aqueous solution called **formalin,** a disinfectant and preservative for biological specimens. As a product of the incomplete combustion of coal and other fossil fuels, formaldehyde is partly responsible for the irritation caused by smoggy air.

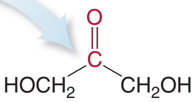
Acetone [$(CH_3)_2C{=}O$, the simplest ketone] is an industrial solvent and a starting material in the synthesis of some organic polymers. Acetone is produced naturally in cells during the breakdown of fatty acids. In diabetes, a disease where normal metabolic processes are altered because of the inadequate secretion of insulin, individuals often have unusually high levels of acetone in the bloodstream. The characteristic odor of acetone can be detected on the breath of diabetic patients when their disease is poorly controlled.

Many aldehydes with characteristic odors occur in nature, as shown in Figure 16.1. It is thought that the shape of these molecules is an important factor in determining their odors, as discussed in Section 15.8.

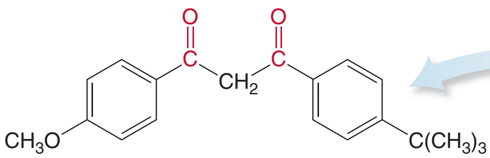
Ketones play an important role in the tanning industry. Dihydroxyacetone is the active ingredient in commercial tanning agents that produce sunless tans. Dihydroxyacetone reacts with proteins in the skin, producing a complex colored pigment that gives the skin a brown hue. In addition, many commercial sunscreens are ketones that have the carbonyl carbon bonded to one or two benzene rings (see also Section 13.11). Examples include avobenzone, oxybenzone, and dioxybenzone.



sunless tanning agent



dihydroxyacetone

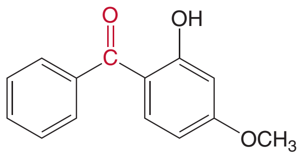


avobenzone

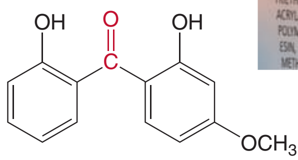


sunscreen

[Ketone carbonyls are shown in red.]



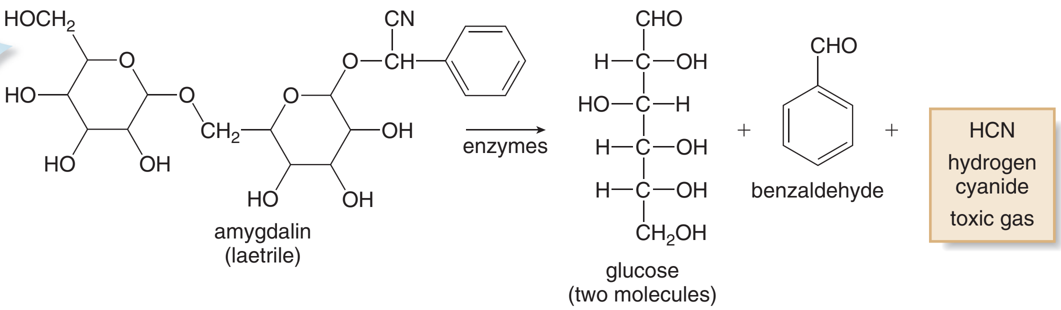
oxybenzone



dioxybenzone

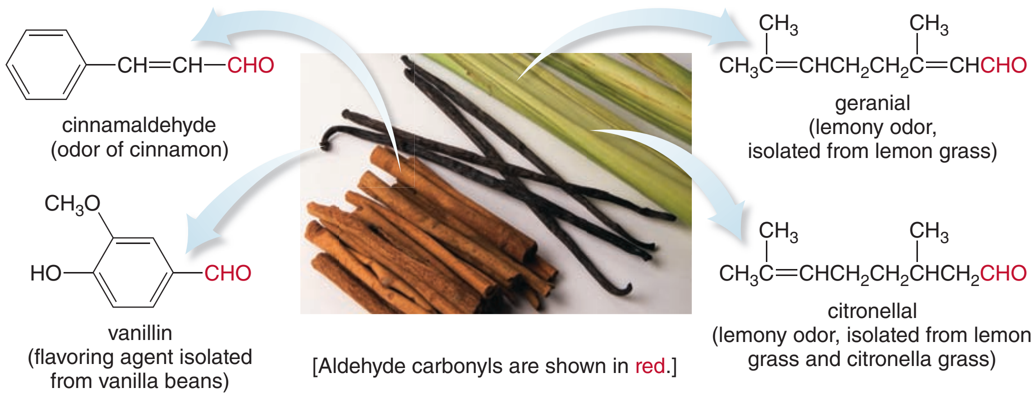
Some naturally occurring compounds do not contain a carbonyl group, but they are converted to aldehydes and ketones by enzymes in cells. One such compound is **amygdalin,** known more commonly as **laetrile.**





Amygdalin is present in the seeds and pits of apricots, peaches, and wild cherries. In the body, amygdalin is converted to two aldehydes, glucose and benzaldehyde. Also formed as a by-product is hydrogen cyanide, **HCN,** a toxic gas. Amygdalin was once touted as an anticancer drug, and is

FIGURE 16.1 Some Naturally Occurring Aldehydes with Characteristic Odors



- **Cinnamaldehyde,** the major component of cinnamon bark, is a common flavoring agent.
- **Vanillin** is the primary component of the extract of the vanilla bean. Because natural sources cannot meet the high demand, most vanilla flavoring agents are made synthetically from starting materials derived from petroleum.
- **Citral** has the lemony odor characteristic of lemon grass. Citral is used in perfumery and as a starting material for synthesizing vitamin A.
- **Citronellal** gives the distinctive lemon odor to citronella candles, commonly used to repel mosquitoes.

still available in some countries for this purpose, although its effectiveness is unproven. It appears as if the toxic HCN produced from amygdalin indiscriminately kills cells without targeting cancer cells. Patients in some clinical trials involving amygdalin show signs of cyanide poisoning but not cancer remission.

PROBLEM 16.11

Acetone [$(CH_3)_2C{=}O$] is a useful solvent because it dissolves a variety of compounds well. For example, both hexane [$CH_3(CH_2)_4CH_3$] and H_2O are soluble in acetone. Explain why these solubility properties are observed.

PROBLEM 16.12

Which sunscreen—avobenzone, oxybenzone, or dioxybenzone—is probably most soluble in water, and therefore most readily washed off when an individual goes swimming? Explain your choice.

16.5 REACTIONS OF ALDEHYDES AND KETONES

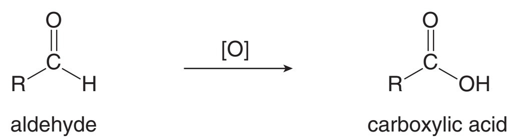
16.5A GENERAL CONSIDERATIONS

Aldehydes and ketones undergo two general types of reactions.

> Aldehydes are easily oxidized by oxygen in the air. When $CH_3CH_2CH_2CHO$ (butanal) stands at room temperature, it slowly develops the characteristic smell of its oxidation product, $CH_3CH_2CH_2COOH$ (butanoic acid), a compound that contributes to the distinctive odor of human sweat.

1. Aldehydes can be oxidized to carboxylic acids.

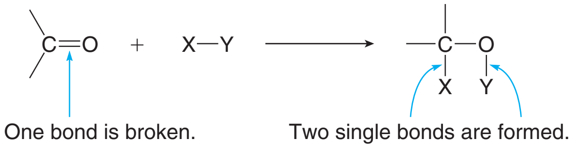
Oxidation



Since aldehydes contain a hydrogen atom bonded to the carbonyl carbon, they can be oxidized to carboxylic acids, as discussed in Section 16.5B.

2. Aldehydes and ketones undergo addition reactions.

Addition



Like alkenes, aldehydes and ketones contain a multiple bond (the carbonyl group) that is readily broken. As a result, aldehydes and ketones undergo addition reactions with a variety of reagents. In the addition reaction, new groups X and Y are added to the carbonyl group of the starting material. One bond of the double bond is broken and two new single bonds are formed. We examine the addition of H_2 in Section 16.6 and the addition of alcohols (ROH) in Section 16.8.

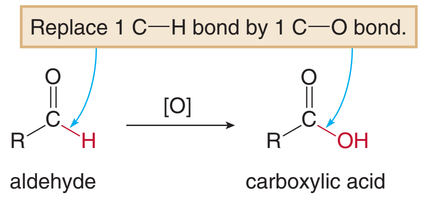
16.5B OXIDATION OF ALDEHYDES



$K_2Cr_2O_7$, potassium dichromate, is used for oxidizing aldehydes, 1° alcohols, and 2° alcohols.

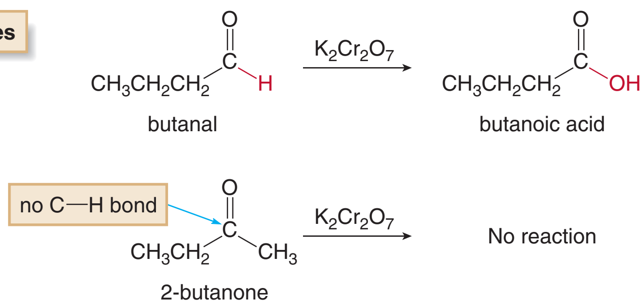
Since aldehydes contain a hydrogen atom bonded directly to the carbonyl carbon, they can be oxidized to carboxylic acids; that is, the aldehyde C—H bond can be converted to a C—OH bond. Since ketones have no hydrogen atom bonded to the carbonyl group, they are not oxidized under similar reaction conditions.

Oxidation



A common reagent for this oxidation is potassium dichromate, $K_2Cr_2O_7$, a red-orange solid that is converted to a green Cr^{3+} product during oxidation.

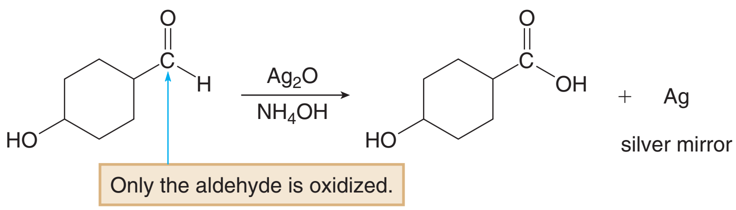
Examples





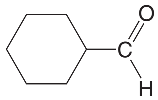
Aldehydes are said to give a *positive* Tollens test; that is, they react with Ag^+ to form RCOOH and Ag. When the reaction is carried out in a glass flask, a silver mirror is formed on its walls. Other functional groups give a *negative* Tollens test; that is, no silver mirror forms.

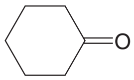
As we learned in Section 14.5, $K_2Cr_2O_7$ oxidizes other functional groups (most notably 1° and 2° alcohols), as well. Aldehydes can be oxidized *selectively* in the presence of other functional groups using **silver(I) oxide (Ag_2O) in aqueous ammonium hydroxide (NH_4OH).** This is called **Tollens reagent.** Only aldehydes react with Tollens reagent; all other functional groups are inert. Oxidation with Tollens reagent provides a distinct color change because the Ag^+ reagent is converted to silver metal (Ag), which precipitates out of the reaction mixture as a silver mirror.



SAMPLE PROBLEM 16.3

What product is formed when each carbonyl compound is treated with $K_2Cr_2O_7$?

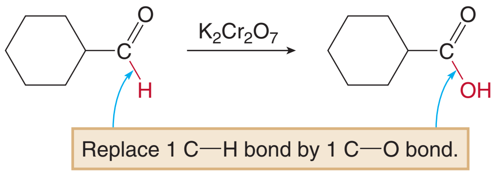
a. 

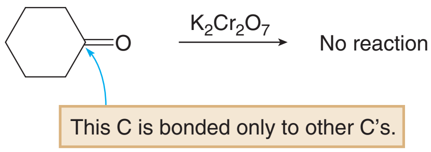
b. 

ANALYSIS Compounds that contain a C—H and C—O bond on the *same* carbon are oxidized with $K_2Cr_2O_7$. Thus:

- Aldehydes (RCHO) are oxidized to RCO_2H.
- Ketones (R_2CO) are not oxidized with $K_2Cr_2O_7$.

SOLUTION The aldehyde in part (a) is oxidized with $K_2Cr_2O_7$ to a carboxylic acid, but the ketone in part (b) is inert to oxidation.

a. 

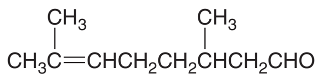
b. 

PROBLEM 16.13

What product is formed when each carbonyl compound is treated with $K_2Cr_2O_7$? In some cases, no reaction occurs.

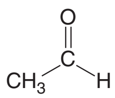
a. CH_3CH_2CHO

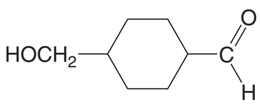
b. $(CH_3CH_2)_2C{=}O$

c. 

SAMPLE PROBLEM 16.4

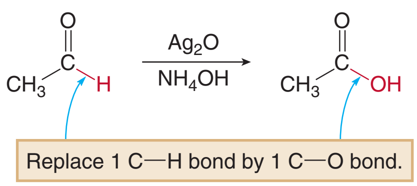
What product is formed when each compound is treated with Tollens reagent (Ag_2O, NH_4OH)?

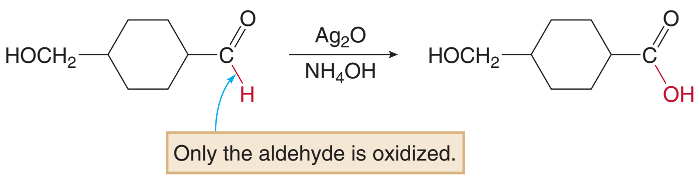
a. 

b. 

ANALYSIS **Only aldehydes (RCHO) react with Tollens reagent.** Ketones and alcohols are inert to oxidation.

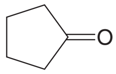
SOLUTION The aldehyde in both compounds is oxidized to RCO_2H, but the 1° alcohol in part (b) does not react with Tollens reagent.

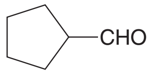
a. 

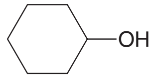
b. 

PROBLEM 16.14 What product is formed when each compound is treated with Tollens reagent (Ag_2O, NH_4OH)? In some cases, no reaction occurs.

a. $CH_3(CH_2)_6CHO$

b. 

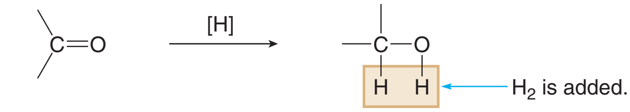
c. 

d. 

16.6 REDUCTION OF ALDEHYDES AND KETONES

Recall from Section 12.8 that to determine if an organic compound has been reduced, we compare the number of C—H and C—O bonds. **Reduction is the *opposite* of oxidation.**

Reduction



carbonyl group — 2 C—O bonds

alcohol — 1 C—O bond, 1 C—H bond

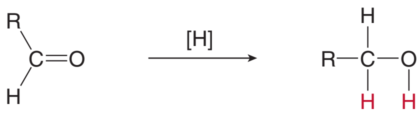
- **Reduction results in a *decrease* in the number of C—O bonds or an *increase* in the number of C—H bonds.**

The conversion of a carbonyl group (C═O) to an alcohol (C—OH) is a reduction, since the starting material has more C—O bonds than the product (two versus one). Reduction of a carbonyl is also an **addition reaction,** since the elements of H_2 are added across the double bond, forming new C—H and O—H bonds. The symbol **[H]** is often used to represent a general reduction reaction.

16.6A SPECIFIC FEATURES OF CARBONYL REDUCTIONS

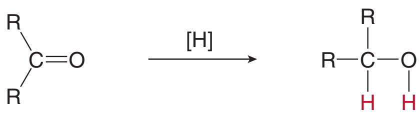
The identity of the carbonyl starting material determines the type of alcohol formed as product in a reduction reaction.

- **Aldehydes (RCHO) are reduced to 1° alcohols (RCH_2OH).**



aldehyde — 1° alcohol

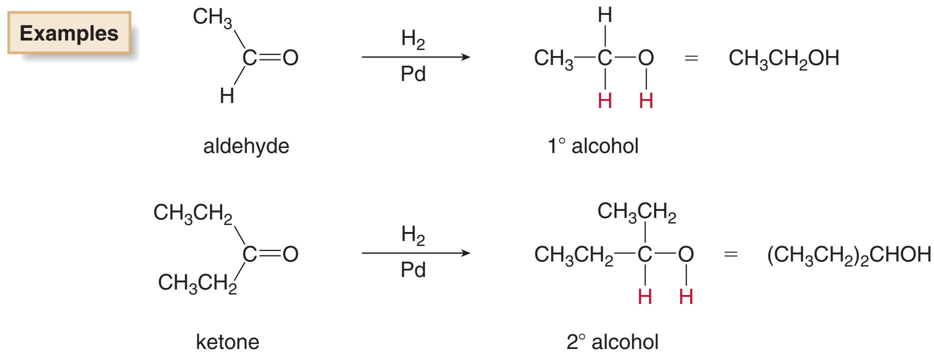
- **Ketones (RCOR) are reduced to 2° alcohols (R_2CHOH).**



ketone — 2° alcohol

Many different reagents can be used to reduce an aldehyde or ketone to an alcohol. For example, the addition of H_2 to a carbonyl group (C═O) takes place with the same reagents used for the addition of H_2 to a C═C—namely, **H_2 gas in the presence of palladium (Pd) metal** (Section 13.6). The metal is a catalyst that provides a surface to bind both the carbonyl compound and H_2,

and this speeds up the rate of reduction. The addition of hydrogen to a multiple bond is called **hydrogenation.**



SAMPLE PROBLEM 16.5

What alcohol is formed when each aldehyde or ketone is treated with H_2 in the presence of a Pd catalyst?



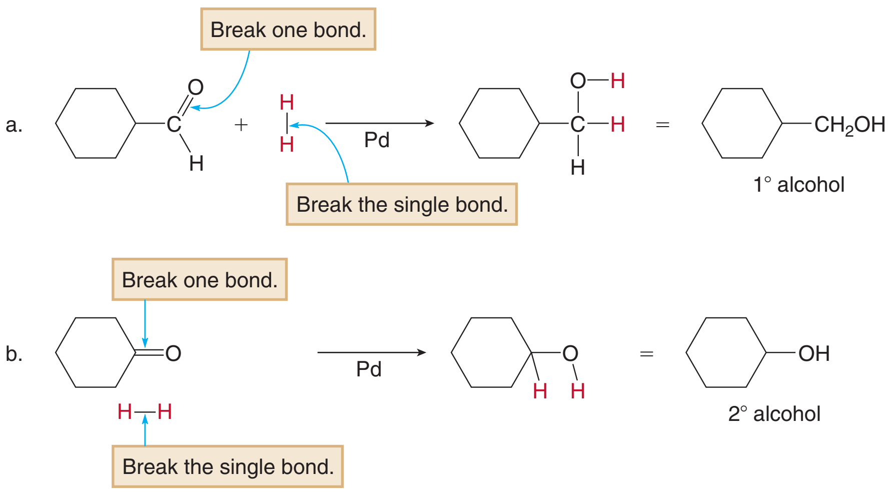
ANALYSIS

To draw the products of reduction:

- Locate the C═O and mentally break one bond in the double bond.
- Mentally break the H—H bond of the reagent.
- Add one H atom to each atom of the C═O, forming new C—H and O—H single bonds.

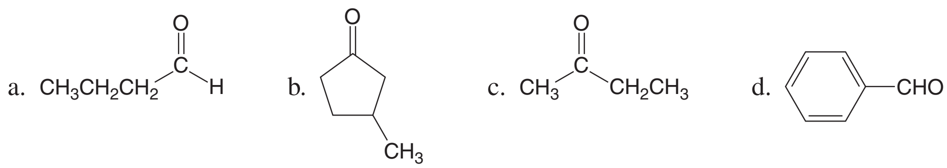
SOLUTION

The aldehyde (RCHO) in part (a) forms a 1° alcohol (RCH_2OH) and the ketone in part (b) forms a 2° alcohol (R_2CHOH).



PROBLEM 16.15

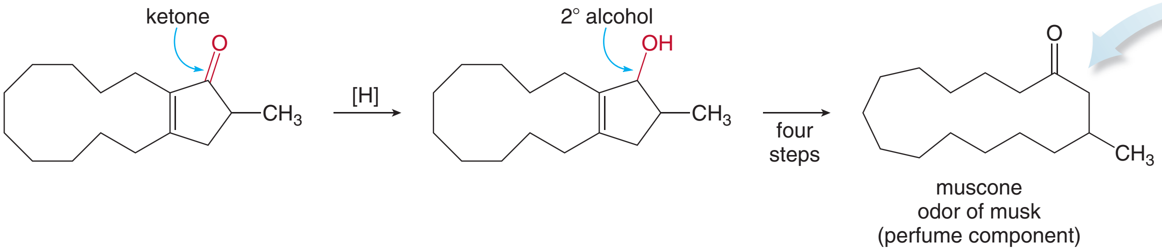
What alcohol is formed when each compound is treated with H_2 and a Pd catalyst?



16.6B EXAMPLES OF CARBONYL REDUCTION IN ORGANIC SYNTHESIS

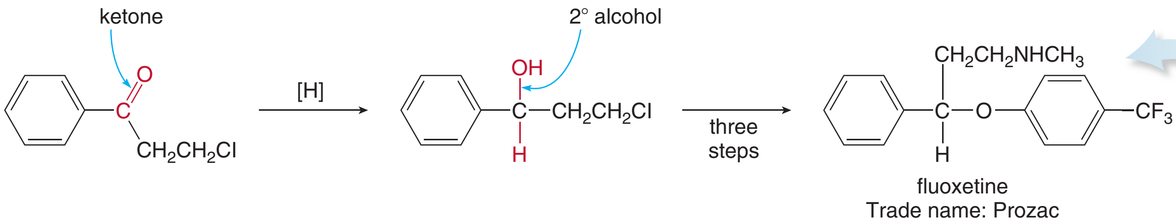
The reduction of aldehydes and ketones is a common reaction used in the laboratory synthesis of many useful compounds.

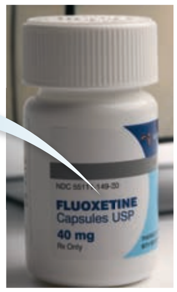
Chemists synthesize compounds for many different reasons. Sometimes a naturally occurring compound has useful properties but is produced by an organism in only minute amounts. Chemists then develop a method to prepare this molecule from simpler starting materials to make it more readily available and less expensive. For example, **muscone,** a strongly scented ketone isolated from musk, is an ingredient in many perfumes. Originally isolated from the male musk deer, muscone is now prepared synthetically in the lab. One step in the synthesis involves reducing a ketone to a 2° alcohol.




male musk deer

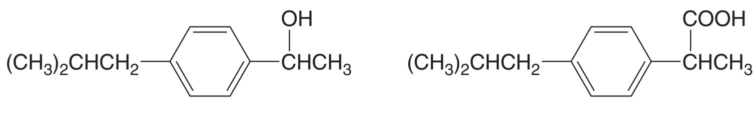
Sometimes chemists prepare molecules that do not occur in nature because they have useful medicinal properties. For example, **fluoxetine** (trade name: Prozac) is a prescription antidepressant that does not occur in nature. One step in a laboratory synthesis of fluoxetine involves reduction of a ketone to a 2° alcohol. Fluoxetine is widely used because it has excellent medicinal properties, *and* because it is readily available by laboratory synthesis.





PROBLEM 16.16

What carbonyl starting material is needed to prepare alcohol **A** by a reduction reaction. **A** can be converted to the anti-inflammatory agent ibuprofen in three steps.



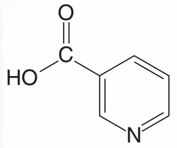
A ibuprofen

16.6C FOCUS ON THE HUMAN BODY BIOLOGICAL REDUCTIONS

The reduction of carbonyl groups is common in biological systems. Biological systems do not use H_2 and Pd as a reducing agent. Instead, they use the coenzyme **NADH** (nicotinamide adenine dinucleotide, reduced form) in the presence of an enzyme. The enzyme binds both the carbonyl

CONSUMER NOTE





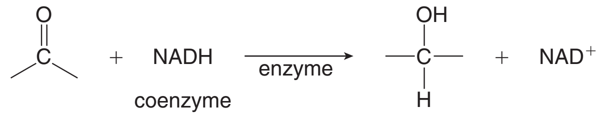
niacin
vitamin B_3



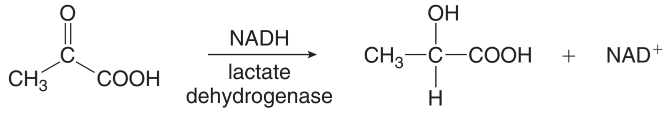
Niacin can be obtained from foods such as soybeans, which contain it naturally, and from breakfast cereals, which are fortified with it.

compound and NADH, holding them closely together, and this facilitates the addition of H_2 to the carbonyl group, forming an alcohol. The NADH itself is oxidized in the process, forming NAD^+. **NAD^+,** a biological oxidizing agent, is a coenzyme synthesized from the vitamin niacin, which can be obtained from soybeans, among other dietary sources.

Biological reduction



For example, the reduction of pyruvic acid with NADH, catalyzed by the enzyme lactate dehydrogenase, yields lactic acid. Pyruvic acid is formed during the metabolism of the simple sugar glucose.



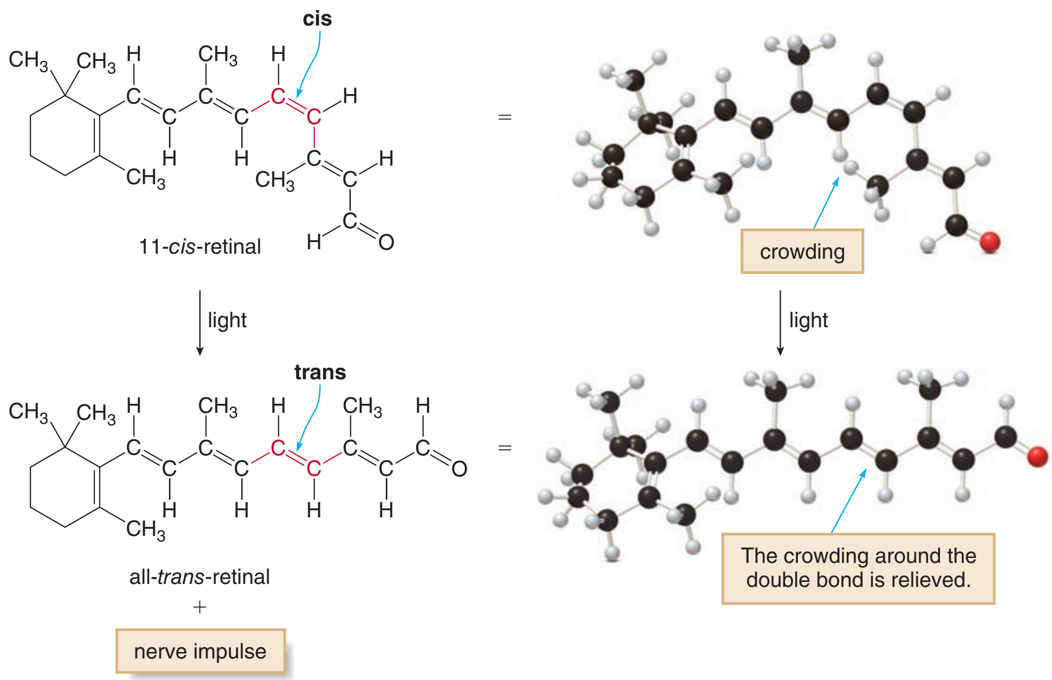
pyruvic acid

lactic acid

16.7 FOCUS ON THE HUMAN BODY THE CHEMISTRY OF VISION

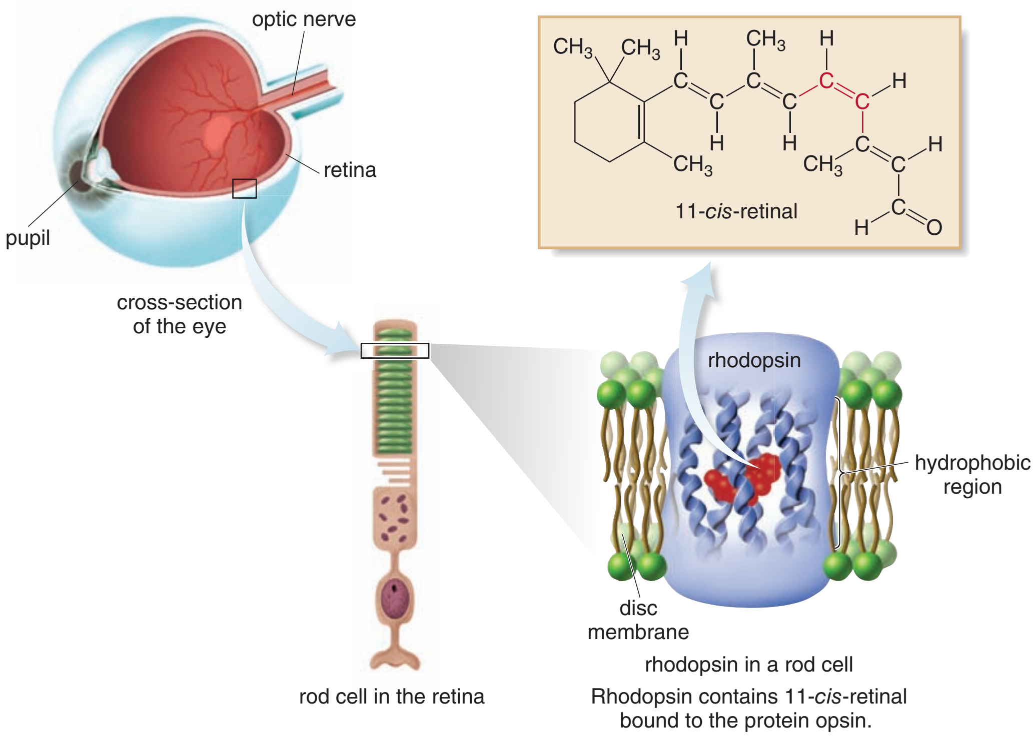
The human eye consists of two types of light-sensitive cells—the rod cells, which are responsible for sight in dim light, and the cone cells, which are responsible for color vision and sight in bright light. Animals like pigeons, whose eyes have only cone cells, have color vision but see poorly in dim light, while owls, which have only rod cells, are color blind but see well in dim light.

The chemistry of vision in the rod cells centers around the aldehyde, **11-*cis*-retinal,** the chapter-opening molecule.



Although 11-*cis*-retinal is a stable molecule, the cis geometry around one of the double bonds causes crowding; a hydrogen atom on one double bond is close to the methyl group on an adjacent double bond. In the human retina (Figure 16.2), 11-*cis*-retinal is bonded to the protein

FIGURE 16.2 Vision



In the rod cells of the eye, the 11-*cis*-retinal bonded to opsin absorbs light, and the crowded 11-cis double bond is isomerized to the trans isomer. This process generates a nerve impulse that is converted to a visual image by the brain.

opsin, forming rhodopsin or visual purple. When light hits the retina, the 11-cis double bond is isomerized to its more stable trans isomer, and all-*trans*-retinal is formed. This process sends a nerve impulse to the brain, which is then converted into a visual image.

In order for the process to continue, the all-*trans*-retinal must be converted back to 11-*cis*-retinal. This occurs by a series of reactions that involve biological oxidation (Section 14.5) and reduction (Section 16.6). As shown in Figure 16.3, NADH is the coenzyme that reduces the aldehyde in all-*trans*-retinal to all-*trans*-retinol, **vitamin A** (Reaction [1]). NAD^+ is the coenzyme that oxidizes 11-*cis*-retinol back to 11-*cis*-retinal (Reaction [3]), so the chemical cycle of vision can continue.

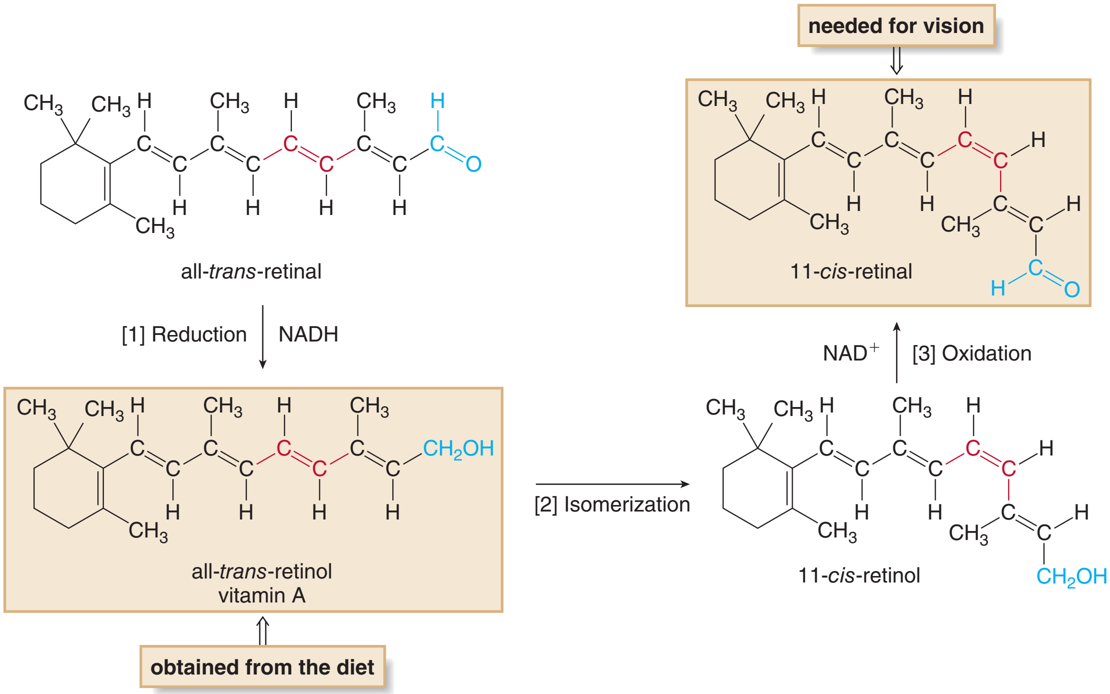
This scheme explains the role of vitamin A (Section 11.7) in vision. Vitamin A can be obtained either directly in the diet or from the orange pigment β-carotene in carrots. Vitamin A, also called all-*trans*-retinol, is converted in two steps to 11-*cis*-retinal, the aldehyde essential for vision in the rod cells. Since the rod cells are responsible for vision in dim light, a deficiency of vitamin A causes night blindness.

PROBLEM 16.17

How are the compounds in each pair related? Choose from stereoisomers, constitutional isomers, or not isomers of each other.

a. all-*trans*-retinal and 11-*cis*-retinal
b. all-*trans*-retinal and vitamin A
c. vitamin A and 11-*cis*-retinol

FIGURE 16.3 Vitamin A and the Chemistry of Vision

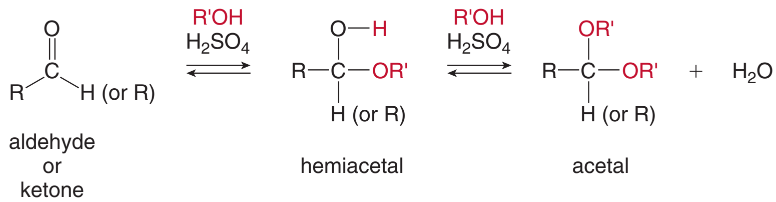


- Reaction [1] (reduction): The aldehyde in all-*trans*-retinal (labeled in blue) is reduced to a 1° alcohol using the coenzyme NADH. The product is all-*trans*-retinol.
- Reaction [2] (isomerization): The trans double bond (labeled in red) is isomerized to a cis double bond, forming 11-*cis*-retinol.
- Reaction [3] (oxidation): The 1° alcohol in 11-*cis*-retinol (labeled in blue) is oxidized with the coenzyme NAD^+ to an aldehyde. This re-forms 11-*cis*-retinal and the chemical cycle of vision continues.

16.8 ACETAL FORMATION

Aldehydes and ketones undergo addition reactions with alcohols (ROH) to form hemiacetals and acetals. Acetal formation is done in the presence of sulfuric acid (H_2SO_4).

Acetal formation



16.8A ACETALS AND HEMIACETALS

Addition of one molecule of alcohol (ROH) to an aldehyde or ketone forms a **hemiacetal.** Like other addition reactions, one bond of the C=O is broken and two new single bonds are formed. Acyclic hemiacetals are unstable. They react with a second molecule of alcohol to form **acetals.**

- A *hemiacetal* contains an OH (hydroxyl) group and an OR (alkoxy) group bonded to the *same* carbon.
- *Acetals* are compounds that contain two OR groups (alkoxy groups) bonded to the *same* carbon.

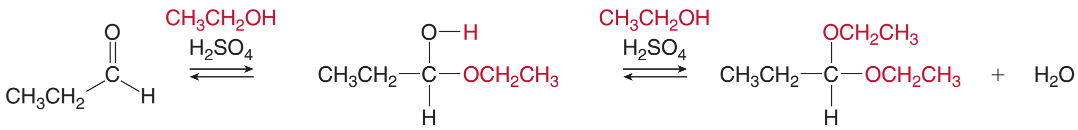


hemiacetal **acetal**

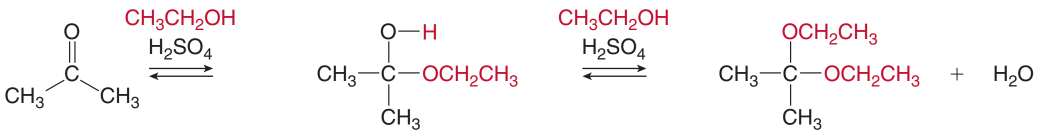
One C is bonded to:
- one OH group
- one OR group

One C is bonded to:
- two OR groups

Two examples of acetal formation using ethanol (CH_3CH_2OH) as the alcohol component are given.



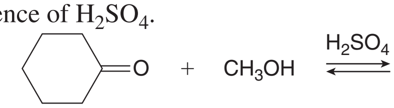
hemiacetal acetal



hemiacetal acetal

SAMPLE PROBLEM 16.6

Draw the hemiacetal and acetal formed when cyclohexanone is treated with methanol (CH_3OH) in the presence of H_2SO_4.

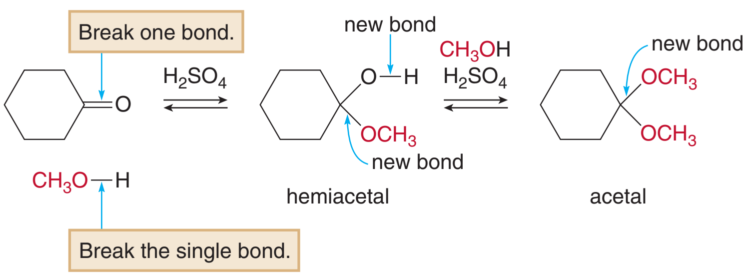


cyclohexanone methanol (2 equivalents)

ANALYSIS To form a hemiacetal and acetal from a carbonyl compound:

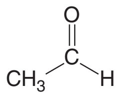
- Locate the C=O in the starting material.
- Break one C—O bond and add one equivalent of CH_3OH across the double bond, placing the OCH_3 group on the carbonyl carbon. This forms the hemiacetal.
- Replace the OH group of the hemiacetal by OCH_3 to form the acetal.

SOLUTION

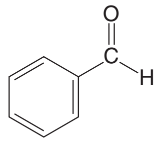


PROBLEM 16.18

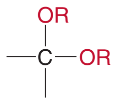
Draw the hemiacetal and acetal formed when each carbonyl compound is treated with two equivalents of the given alcohol in the presence of H_2SO_4.

a.  + CH_3OH

b. $(CH_3CH_2)_2C{=}O$ + CH_3OH

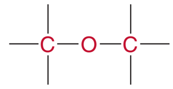
c.  + CH_3CH_2OH

Acetals are *not* ethers, even though both compounds contain a C—OR bond.



acetal

2 OR groups on one carbon



ether

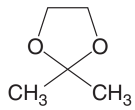
2 C's on a single O atom

- **An acetal contains one carbon atom bonded to *two* OR groups.**
- **An ether contains only *one* oxygen atom bonded to two carbons.**

SAMPLE PROBLEM 16.7

Identify each compound as an ether, hemiacetal, or acetal.

a. $CH_3CH_2—O—CH_2CH_3$

b. 

ANALYSIS Recall the definitions to identify the functional groups:

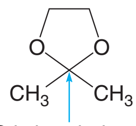
- An ether has the general structure ROR.
- A hemiacetal has one C bonded to OH and OR.
- An acetal has one C bonded to two OR groups.

SOLUTION

a. $CH_3CH_2—O—CH_2CH_3$

2 C's on one O atom

ether

b. 

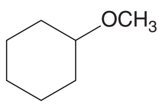
This C is bonded to 2 O's.

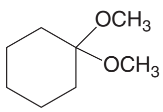
acetal

Note that the acetal in part (b) is part of a ring. It contains one ring carbon bonded to two oxygens, making it an acetal.

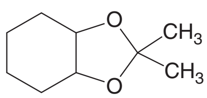
PROBLEM 16.19

Identify each compound as an ether, hemiacetal, or acetal.

a. 

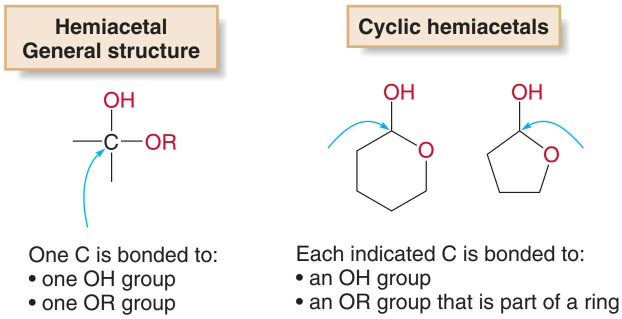
b. 

c. $CH_3CH_2CH_2CH_2—C(OH)(H)—OCH_3$

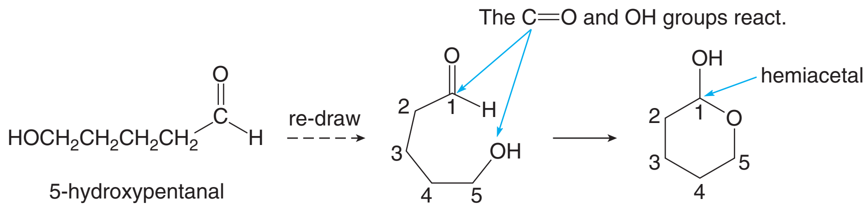
d. 

16.8B CYCLIC HEMIACETALS

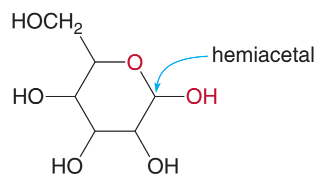
Although acyclic hemiacetals are generally unstable, **cyclic hemiacetals containing five- and six-membered rings are stable compounds** that are readily isolated.



These cyclic hemiacetals are formed by an ***intramolecular*** reaction of a compound that contains *both* a hydroxyl group and an aldehyde or ketone.

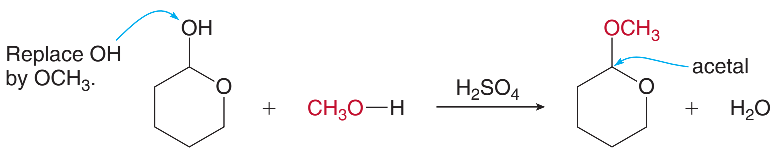


Cyclic hemiacetals are especially important in carbohydrate chemistry. **The most common simple carbohydrate, glucose, exists predominantly as a cyclic hemiacetal.** Glucose has five OH groups, but only one OH group is bonded to a carbon that is also bonded to another oxygen atom, making it a hemiacetal. All of the other OH groups in glucose are "regular" alcohols. We will learn much more about these stable cyclic hemiacetals in Chapter 20.

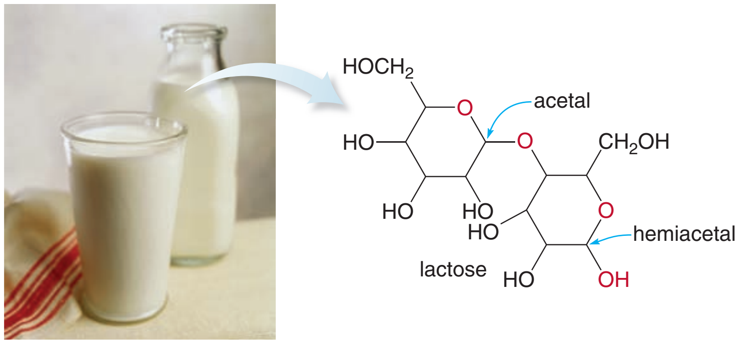


glucose
(cyclic hemiacetal form)

Cyclic hemiacetals are converted to acetals by reaction with another alcohol (ROH). To draw the structure of the resulting acetal, replace the OH group of the hemiacetal by the OR group of the alcohol.

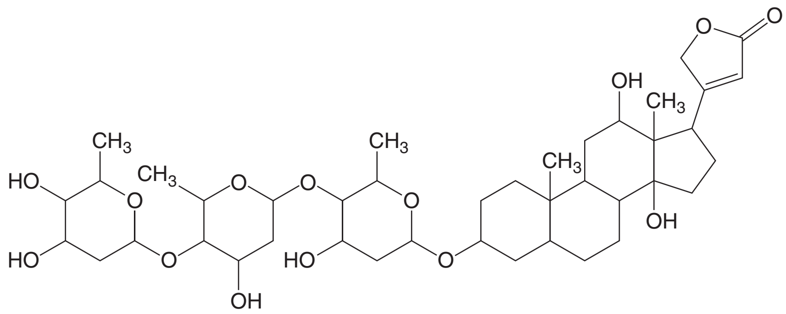


Many biologically active molecules contain acetals and cyclic hemiacetals. For example, lactose, the principal carbohydrate in milk, contains one acetal and one hemiacetal. Many individuals, mainly of Asian and African descent, lack adequate amounts of lactase, the enzyme needed to digest and absorb lactose. This condition, lactose intolerance, is associated with abdominal cramping and recurrent diarrhea.



SAMPLE PROBLEM 16.8

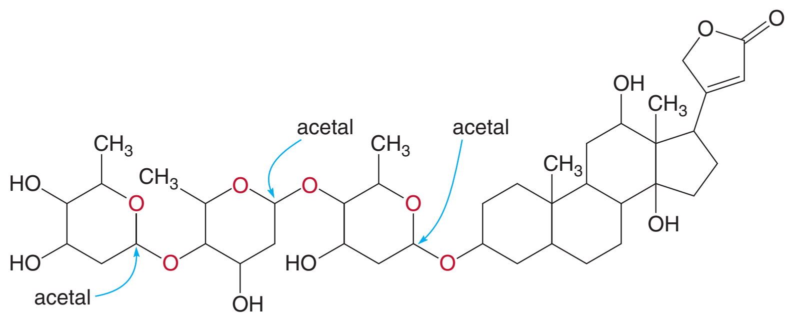
Identify the three acetals in digoxin, a naturally occurring drug prescribed for patients with congestive heart failure and other heart ailments.



digoxin

ANALYSIS Although the structure of digoxin is complicated, look at each O atom individually and recall that an **acetal has one C bonded to two OR groups.**

SOLUTION The acetal carbons in digoxin are indicated with arrows and the oxygen atoms of the acetals are drawn in red.



digoxin

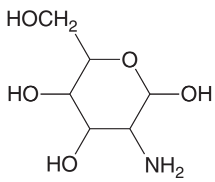
HEALTH NOTE



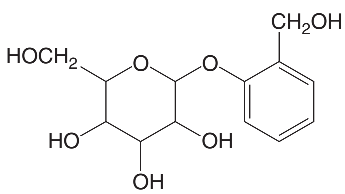
The leaves of the woolly foxglove plant are the source of the potent cardiac drug digoxin.

PROBLEM 16.20

Label the hemiacetal or acetal in each compound. Glucosamine [part (a)] is available in many over-the-counter remedies for the treatment of osteoarthritis, although recent studies cast doubt on its efficacy. Salicin [part (b)] is a naturally occurring pain reliever isolated from the bark of the willow tree.

a. 

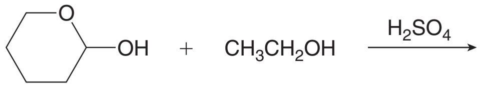
glucosamine

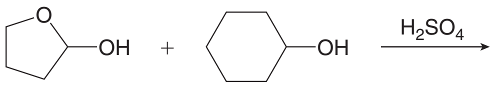
b. 

salicin

PROBLEM 16.21

What acetal is formed in each reaction?

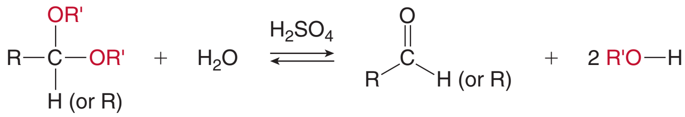
a. 

b. 

16.8C ACETAL HYDROLYSIS

Acetals are stable molecules, but they can be converted back to aldehydes and ketones by treatment with acid and water. This reaction is a ***hydrolysis*, since bonds are cleaved by reaction with water.**

Acetal hydrolysis



aldehyde
or
ketone

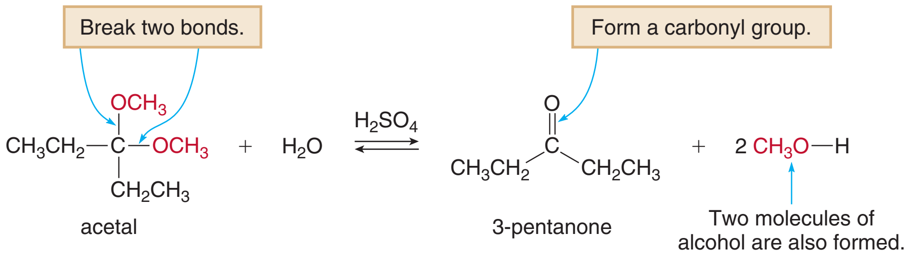
SAMPLE PROBLEM 16.9

What hydrolysis products are formed when the acetal $(CH_3CH_2)_2C(OCH_3)_2$ is treated with H_2SO_4 in H_2O?

ANALYSIS To draw the products of hydrolysis:

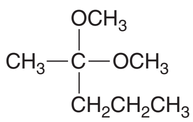
- Locate the two C—OR bonds on the same carbon.
- Replace the two C—O single bonds with a carbonyl group (C═O).
- Each OR group then becomes a molecule of alcohol (ROH) product.

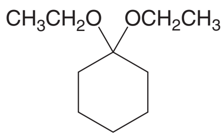
SOLUTION

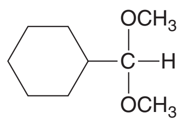


PROBLEM 16.22

What products are formed by hydrolysis of each acetal?

a. 

b. 

c. 

CHAPTER HIGHLIGHTS

KEY TERMS

Acetal (16.8)
Aldehyde (16.1)
Carbonyl group (16.1)
Cyclic hemiacetal (16.8)
Hemiacetal (16.8)
Hydrogenation (16.6)
Hydrolysis (16.8)
Ketone (16.1)
NAD^+ (16.6)
NADH (16.6)
Oxidation (16.5)
Reduction (16.6)
Tollens reagent (16.5)

KEY REACTIONS

[1] Oxidation of aldehydes (16.5)

$$RCHO \xrightarrow[\text{or Tollens reagent}]{K_2Cr_2O_7} \underset{\text{carboxylic acid}}{RCOOH}$$

[2] Reduction (16.6)

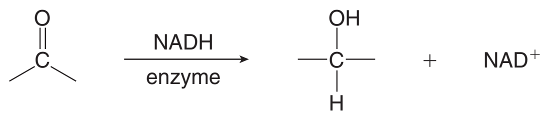
a. Aldehydes

$$RCHO \xrightarrow[Pd]{H_2} \underset{1^\circ \text{ alcohol}}{RCH_2OH}$$

b. Ketones

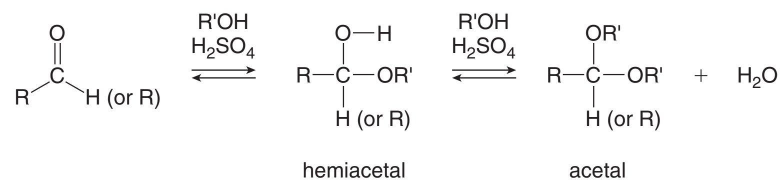
$$R_2CO \xrightarrow[Pd]{H_2} \underset{2^\circ \text{ alcohol}}{R_2CHOH}$$

c. Biological reduction

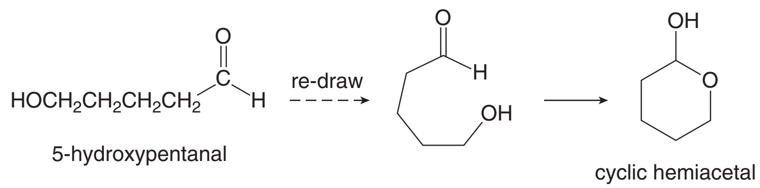


[3] Acetals and hemiacetals (16.8)

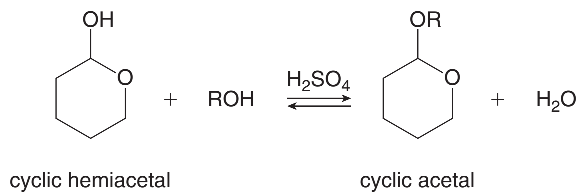
a. General reaction



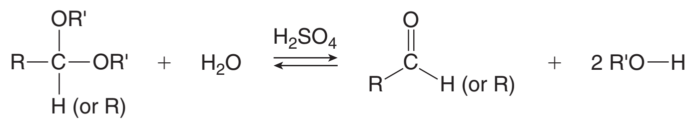
b. Cyclic hemiacetal



c. Cyclic acetals



d. Acetal hydrolysis



KEY CONCEPTS

1 What are the characteristics of aldehydes and ketones?

- An aldehyde has the general structure RCHO, and contains a carbonyl group (C═O) bonded to at least one hydrogen atom. (16.1)
- A ketone has the general structure RCOR', and contains a carbonyl group (C═O) bonded to two carbon atoms. (16.1)
- The carbonyl carbon is trigonal planar, with bond angles of approximately 120°. (16.1)
- The carbonyl group is polar, giving an aldehyde or ketone stronger intermolecular forces than hydrocarbons. (16.3)
- Aldehydes and ketones have lower boiling points than alcohols, but higher boiling points than hydrocarbons of comparable size. (16.3)
- Aldehydes and ketones are soluble in organic solvents, but those having less than six C's are water soluble, too. (16.3)

2 How are aldehydes and ketones named? (16.2)

- Aldehydes are identified by the suffix *-al,* and the carbon chain is numbered to put the carbonyl group at C1.
- Ketones are identified by the suffix *-one,* and the carbon chain is numbered to give the carbonyl group the lower number.

3 Give examples of useful aldehydes and ketones. (16.4)

- Formaldehyde (CH_2═O) is an irritant in smoggy air, a preservative, and a disinfectant, and it is a starting material for synthesizing polymers.
- Acetone [$(CH_3)_2$C═O] is an industrial solvent and polymer starting material.
- Several aldehydes—cinnamaldehyde, vanillin, citral, and citronellal—have characteristic odors and occur naturally in fruits and plants.
- Dihydroxyacetone [$(HOCH_2)_2$C═O] is the active ingredient in artificial tanning agents, and many other ketones are useful sunscreens.
- Amygdalin, a naturally occurring carbonyl derivative, forms toxic HCN on hydrolysis.

4 What products are formed when aldehydes are oxidized? (16.5)

- Aldehydes are oxidized to carboxylic acids (RCOOH) with $K_2Cr_2O_7$ or Tollens reagent.
- Ketones are not oxidized since they contain no H atom on the carbonyl carbon.

5 What products are formed when aldehydes and ketones are reduced? (16.6)

- Aldehydes are reduced to 1° alcohols with H_2 and a Pd catalyst.
- Ketones are reduced to 2° alcohols with H_2 and a Pd catalyst.
- Biological reduction occurs with the coenzyme NADH.

6 What reactions occur during vision? (16.7)

- When light hits the retina, the crowded C═C in 11-*cis*-retinal is isomerized to a more stable trans double bond, and a nerve impulse is generated. All-*trans*-retinal is converted back to the cis isomer by a three-step sequence—reduction, isomerization, and oxidation.

7 What are hemiacetals and acetals, and how are they prepared? (16.8)

- Hemiacetals contain an OH group and an OR group bonded to the same carbon.
- Acetals contain two OR groups bonded to the same carbon.
- Treatment of an aldehyde or ketone with an alcohol (ROH) first forms an unstable hemiacetal, which reacts with more alcohol to form an acetal.
- Cyclic hemiacetals are stable compounds present in carbohydrates and some drugs.
- Acetals are converted back to aldehydes and ketones by hydrolysis with water and acid.

PROBLEMS

Selected in-chapter and end-of-chapter problems have brief answers provided in Appendix B.

Structure and Bonding

16.23 Draw the structure of a compound that fits each description:
a. an aldehyde of molecular formula $C_8H_{16}O$ that has six carbons in its longest chain
b. a ketone of molecular formula $C_6H_{12}O$ that contains five carbons in its longest chain
c. a ketone of molecular formula C_5H_8O that contains a ring
d. an aldehyde of molecular formula $C_6H_{10}O$ that has the CHO group bonded to a ring

16.24 Draw the structure of a constitutional isomer of 2-heptanone ($CH_3COCH_2CH_2CH_2CH_2CH_3$) that:
a. contains an aldehyde
b. contains a ketone
c. contains a hydroxyl group (OH)

16.25 How do a C═O and a C═C compare with regards to the following: (a) geometry; (b) polarity; (c) type of reaction?

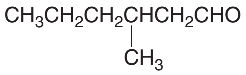
16.26 How do an aldehyde and a ketone compare in (a) structure; (b) geometry; (c) polarity?

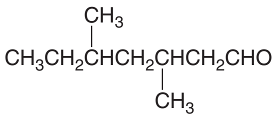
16.27 Can an aldehyde have molecular formula $C_5H_{12}O$? Explain why or why not.

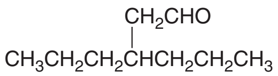
16.28 Can a ketone have molecular formula $C_4H_{10}O$? Explain why or why not.

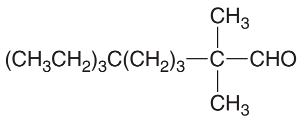
Nomenclature

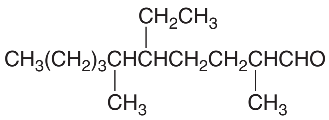
16.29 Give an acceptable name for each aldehyde.

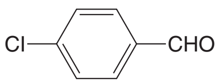
a. 

b. 

c. 

d. 

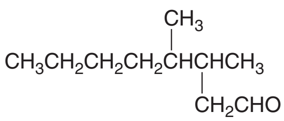
e. 

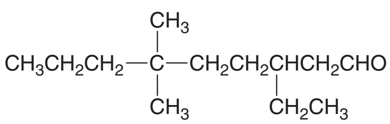
f. 

16.30 Give an acceptable name for each aldehyde.

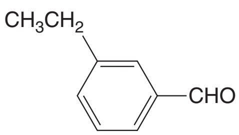
a. $(CH_3)_3CCH_2CHO$

b. $(CH_3CH_2)_2CHCH_2CH_2CHO$

c. 

d. 

e. $(CH_3CH_2CH_2CH_2)_2CHCH_2CHO$

f. 

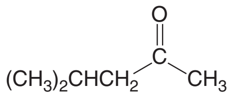
16.31 Draw the structure corresponding to each name.

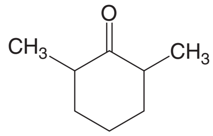
a. 3,3-dichloropentanal
b. 3,4-dimethylhexanal
c. *o*-bromobenzaldehyde
d. 4-hydroxyheptanal

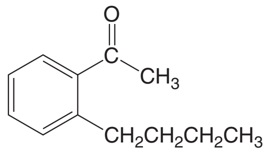
16.32 Draw the structure corresponding to each name.

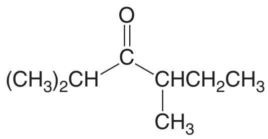
a. 2-bromooctanal
b. 2-propylheptanal
c. 3,4-dimethoxybenzaldehyde
d. 3,4-dihydroxynonanal

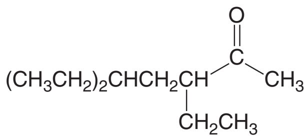
16.33 Give an acceptable name for each ketone.

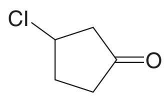
a. 

b. 

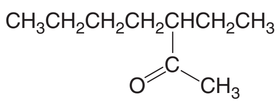
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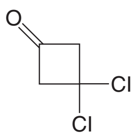
d. 

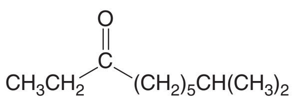
e. 

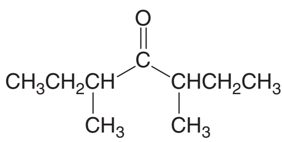
f. 

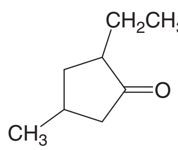
16.34 Give an acceptable name for each ketone.

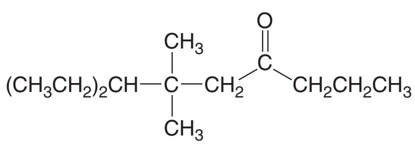
a. 

b. 

c. 

d. 

e. 

f. 

16.35 Draw the structure corresponding to each name.
a. 3,3-dimethyl-2-hexanone
b. methyl propyl ketone
c. *m*-ethylacetophenone
d. 2,4,5-triethylcyclohexanone

16.36 Draw the structure corresponding to each name.
a. dibutyl ketone
b. 1-chloro-3-pentanone
c. *p*-bromoacetophenone
d. 3-hydroxycyclopentanone

16.37 Draw the structure of the four constitutional isomers of molecular formula $C_6H_{12}O$ that contain an aldehyde and four carbons in the longest chain. Give the IUPAC name for each aldehyde.

16.38 Draw the structure of the three isomeric ketones of molecular formula $C_5H_{10}O$. Give the IUPAC name for each ketone.

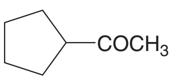
16.39 Each of the following names is incorrect. Draw the structure of the compound and name it correctly.
a. 1-pentanone
b. 4-hexanone
c. 3-propyl-2-butanone
d. 2-methyl-1-octanal

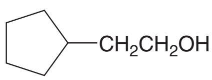
16.40 Each of the following names is incorrect. Draw the structure of the compound and name it correctly.
a. 6-octanone
b. 1-heptanone
c. 3-propyl-1-cyclopentanone
d. 5-methylcyclohexanone

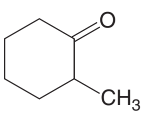
Physical Properties and Intermolecular Forces

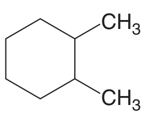
16.41 Draw out the structure of benzaldehyde, including any lone pairs on oxygen. Then, show the hydrogen bonding interactions between benzaldehyde and water.

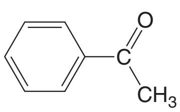
16.42 Can hydrogen bonding occur between the compounds in each pair? If hydrogen bonding is possible, draw out the compounds and indicate how that interaction would take place.
a. two molecules of acetaldehyde (CH_3CHO)
b. CH_3CHO and H_2O
c. CH_3CHO and CH_3OH

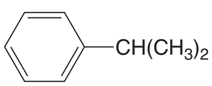
16.43 Which compound in each pair has the higher boiling point?
a. $(CH_3)_3CCH_2CH_2CH_3$ or $(CH_3)_3CCH_2CHO$
b. 

or 

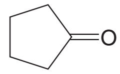
c. 

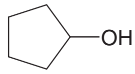
or 

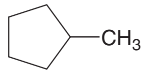
16.44 Which compound in each pair has the higher boiling point?
a. $CH_3(CH_2)_6CHO$ or $CH_3(CH_2)_7OH$
b. $CH_3(CH_2)_6CHO$ or $CH_3(CH_2)_2CHO$
c. 

or 

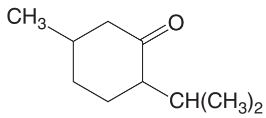
16.45 Rank the following compounds in order of increasing melting point.



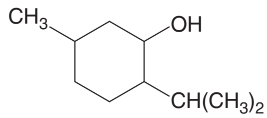




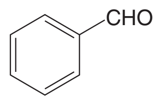
16.46 Menthone and menthol are both isolated from mint. Explain why menthol is a solid at room temperature but menthone is a liquid.

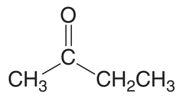


menthone

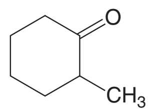


menthol

16.47 Label each compound as water soluble or water insoluble.
a. 

b. 

c. $CH_3CH_2CH_2CH_3$

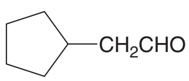
16.48 Label each compound as water soluble or water insoluble.
a. 

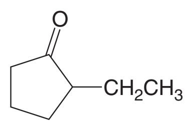
b. $CH_3CH_2CH_2CHO$
c. $CH_3CH_2CH_2OH$

16.49 Explain why 2,3-butanedione ($CH_3COCOCH_3$) is more soluble in water than acetone [$(CH_3)_2CO$] even though it has more carbon atoms. Would you expect 2,3-butanedione to be soluble in an organic solvent like diethyl ether?

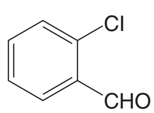
16.50 Explain why the simplest ketone, acetone, has a much higher boiling point than the simplest aldehyde, formaldehyde.

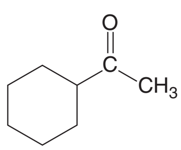
Oxidation and Reduction

16.51 What product is formed when each compound is treated with $K_2Cr_2O_7$? With some compounds, no reaction occurs.
a. $CH_3(CH_2)_4CHO$
b. 

c. 

d. $CH_3(CH_2)_4CH_2OH$

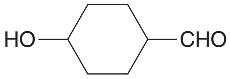
16.52 What product is formed when each compound is treated with $K_2Cr_2O_7$? With some compounds, no reaction occurs.
a. 

b. $CH_3(CH_2)_8CHO$
c. $CH_3\overset{OH}{C}HCH_2CH_2CH_3$
d. 

16.53 What product is formed when each compound in Problem 16.51 is treated with Tollens reagent (Ag_2O, NH_4OH)? With some compounds, no reaction occurs.

16.54 What product is formed when each compound in Problem 16.52 is treated with Tollens reagent (Ag_2O, NH_4OH)? With some compounds, no reaction occurs.

16.55 What compound is formed when hydroxy aldehyde **A** is treated separately with each oxidizing agent?



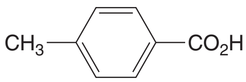
A

a. $K_2Cr_2O_7$
b. Ag_2O, NH_4OH

16.56 (a) Give the structure of a compound of molecular formula C_4H_8O that reacts with Tollens reagent but not $K_2Cr_2O_7$. (b) Give the structure of a compound of molecular formula C_4H_8O that reacts with $K_2Cr_2O_7$ but not Tollens reagent.

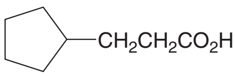
16.57 What aldehyde is needed to prepare each carboxylic acid by an oxidation reaction?

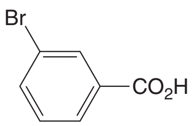
a. $CH_3CH_2\overset{CH_3}{\overset{|}{C}}HCH_2CO_2H$

b. 

c. $CH_3CH_2\underset{CO_2H}{\underset{|}{C}}HCH_2CH_3$

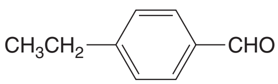
16.58 What aldehyde is needed to prepare each carboxylic acid by an oxidation reaction?

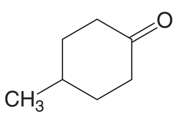
a. 

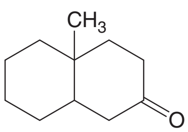
b. 

c. $CH_3(CH_2)_8\overset{Cl}{\overset{|}{C}}HCO_2H$

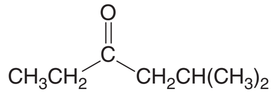
16.59 What alcohol is formed when each carbonyl compound is treated with H_2 and a Pd catalyst?

a. 

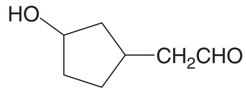
b. 

c. 

16.60 What alcohol is formed when each carbonyl compound is treated with H_2 and a Pd catalyst?

a. 

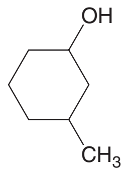
b. $CH_3(CH_2)_6CHO$

c. 

16.61 What carbonyl compound is needed to make each alcohol by a reduction reaction?

a. CH_3OH

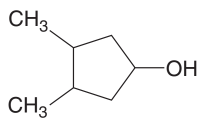
b. $CH_3CH_2CH_2CH_2CH_2OH$

c. 

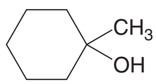
16.62 What carbonyl compound is needed to make each alcohol by a reduction reaction?

a. $CH_3CH_2\overset{OH}{\overset{|}{C}}HCH_2CH_2CH_3$

b. $(CH_3)_2CHCH_2CH_2OH$

c. 

16.63 Why can't 1-methylcyclohexanol be prepared by the reduction of a carbonyl compound?



1-methylcyclohexanol

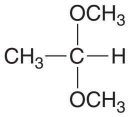
16.64 Why can't $(CH_3)_3COH$ be prepared by the reduction of a carbonyl compound?

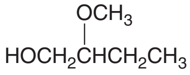
Hemiacetals and Acetals

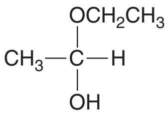
16.65 Draw the structure of a compound of molecular formula $C_5H_{12}O_2$ that fits each description.
a. a compound that contains an acetal
b. a compound that contains a hemiacetal
c. a compound that contains two ethers
d. a compound that contains an alcohol and an ether, but is not a hemiacetal

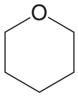
16.66 Locate the two acetals in amygdalin (Section 16.4).

16.67 Label each functional group as an alcohol, ether, acetal, or hemiacetal.

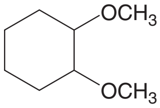
a. 

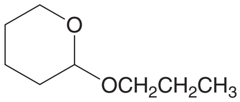
c. 

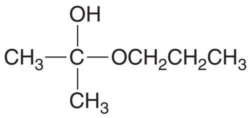
b. 

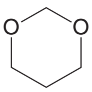
d. 

16.68 Label each functional group as an alcohol, ether, acetal, or hemiacetal.

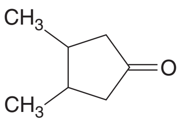
a. 

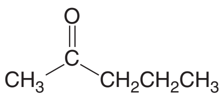
c. 

b. 

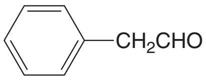
d. 

16.69 What acetal is formed when each aldehyde or ketone is treated with two equivalents of methanol (CH_3OH) in the presence of H_2SO_4?

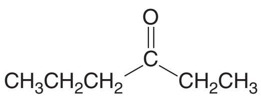
a. 

c. 

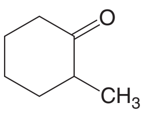
b. $CH_2{=}O$

d. 

16.70 What acetal is formed when each aldehyde or ketone is treated with two equivalents of ethanol (CH_3CH_2OH) in the presence of H_2SO_4?

a. 

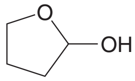
c. $(CH_3)_2CHCH_2CH_2CHO$

b. 

d. CH_3CH_2CHO

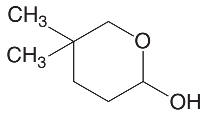
16.71 (a) What hemiacetal is formed when acetone [$(CH_3)_2CO$] is treated with one equivalent of cyclopentanol? (b) What acetal is formed when acetone is treated with two equivalents of cyclopentanol in the presence of H_2SO_4?

16.72 (a) What hemiacetal is formed when benzaldehyde (C_6H_5CHO) is treated with one equivalent of cyclohexanol? (b) What acetal is formed when benzaldehyde is treated with two equivalents of cyclohexanol in the presence of H_2SO_4?

16.73 

A

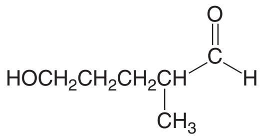
a. Identify the hemiacetal carbon in compound **A.**
b. What hydroxy aldehyde would form this hemiacetal in a cyclization reaction?
c. What product is formed when **A** is treated with CH_3OH and H_2SO_4?

16.74 

B

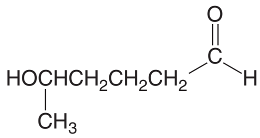
a. Identify the hemiacetal carbon in compound **B.**
b. What hydroxy aldehyde would form this hemiacetal in a cyclization reaction?
c. What product is formed when **B** is treated with CH_3CH_2OH and H_2SO_4?

16.75 What hemiacetal is formed when hydroxy aldehyde **C** is cyclized?



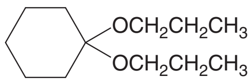
C

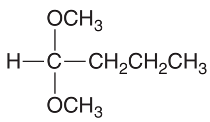
16.76 What hemiacetal is formed when hydroxy aldehyde **D** is cyclized?



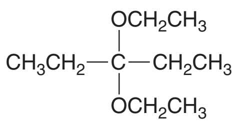
D

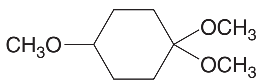
16.77 What products are formed when each acetal is hydrolyzed with water and sulfuric acid?

a. 

b. 

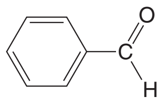
16.78 What products are formed when each acetal is hydrolyzed with water and sulfuric acid?

a. 

b. 

General Reactions

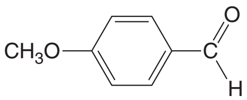
16.79 Benzaldehyde is the compound principally responsible for the odor of almonds. What products are formed when benzaldehyde is treated with each reagent?



benzaldehyde

a. H_2, Pd
b. $K_2Cr_2O_7$
c. Ag_2O, NH_4OH
d. CH_3OH (2 equivalents), H_2SO_4
e. CH_3CH_2OH (2 equivalents), H_2SO_4
f. Product in (e), then H_2O, H_2SO_4

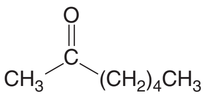
16.80 Anisaldehyde is a component of anise, a spice with a licorice odor used in cooking and aromatherapy. What products are formed when anisaldehyde is treated with each reagent?



anisaldehyde

a. H_2, Pd
b. $K_2Cr_2O_7$
c. Ag_2O, NH_4OH
d. CH_3OH (2 equivalents), H_2SO_4
e. CH_3CH_2OH (2 equivalents), H_2SO_4
f. Product in (e), then H_2O, H_2SO_4

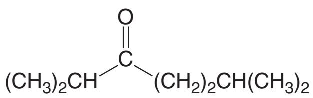
16.81 2-Heptanone is an alarm pheromone of the bee. What products are formed when 2-heptanone is treated with each reagent? With some reagents, no reaction occurs.



2-heptanone

a. H_2, Pd
b. $K_2Cr_2O_7$
c. Ag_2O, NH_4OH
d. CH_3OH (2 equivalents), H_2SO_4
e. CH_3CH_2OH (2 equivalents), H_2SO_4
f. Product in (e), then H_2O, H_2SO_4

16.82 2,6-Dimethyl-3-heptanone is a communication pheromone of the bee. What products are formed when 2,6-dimethyl-3-heptanone is treated with each reagent? With some reagents, no reaction occurs.

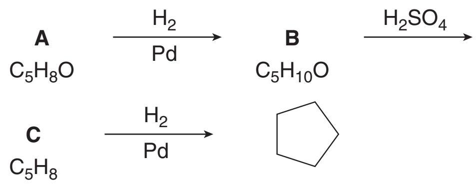


2,6-dimethyl-3-heptanone

a. H_2, Pd
b. $K_2Cr_2O_7$
c. Ag_2O, NH_4OH
d. CH_3OH (2 equivalents), H_2SO_4
e. CH_3CH_2OH (2 equivalents), H_2SO_4
f. Product in (e), then H_2O, H_2SO_4

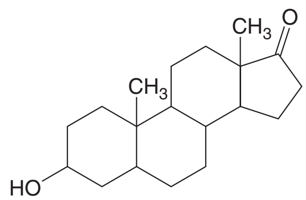
16.83 Three constitutional isomers of molecular formula C_5H_8O can be converted to 1-pentanol ($CH_3CH_2CH_2CH_2CH_2OH$) on treatment with two equivalents of H_2 in the presence of a Pd catalyst. Draw the structures of the three possible compounds, all of which contain a carbonyl group.

16.84 Identify **A–C** in the following reaction sequence.



Applications

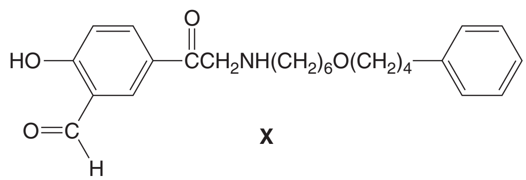
16.85 Androsterone is a male sex hormone that controls the development of secondary sex characteristics in males. Draw the organic products formed when androsterone is treated with each reagent.



androsterone

a. H_2, Pd
b. $K_2Cr_2O_7$
c. CH_3OH (2 equivalents), H_2SO_4
d. CH_3CH_2OH (2 equivalents), H_2SO_4

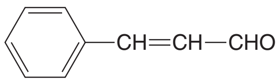
16.86 Salmeterol (trade name: Serevent) is a drug that dilates airways and is used to treat asthma. It can be formed by the reduction of a dicarbonyl compound **X** with excess H_2 and a Pd catalyst.



X

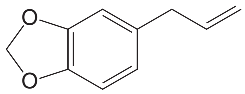
a. Draw the structure of salmeterol.
b. Label the one chirality center in salmeterol.
c. Draw both enantiomers of salmeterol in three dimensions using wedges and dashes (see Section 15.3).

16.87 When cinnamon is ingested, the cinnamaldehyde it contains is oxidized by the coenzyme NAD^+ and an enzyme in a similar fashion to the biological oxidation described in Section 14.6. What oxidation product is formed from cinnamaldehyde?



cinnamaldehyde

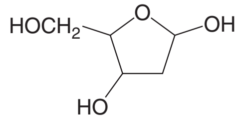
16.88 Safrole is a naturally occurring compound isolated from sassafras plants. Once used as a common food additive in root beer and other beverages, it is now banned because it is carcinogenic.



safrole

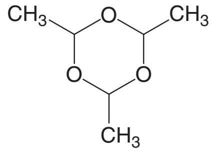
a. Label the functional groups in safrole.
b. What products are formed when safrole undergoes hydrolysis with water and sulfuric acid?

16.89 2-Deoxyribose is a building block of DNA, very large organic molecules that store all genetic information. Label each OH group in 2-deoxyribose as being part of a regular alcohol or a hemiacetal.



2-deoxyribose

16.90 Paraldehyde, a hypnotic and sedative once commonly used to treat seizures and induce sleep in some hospitalized patients, is formed from three molecules of acetaldehyde (CH_3CHO). Label the acetal carbons in paraldehyde.



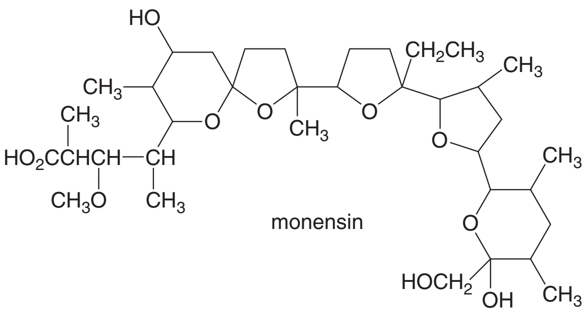
paraldehyde

16.91 Describe the main reaction that occurs in the rod cells in the retina, which generates a nerve impulse that allows us to see. What role does the geometry of 11-*cis*-retinal play in this process?

16.92 What reactions convert all-*trans*-retinal back to 11-*cis*-retinal so that the process of vision can continue?

CHALLENGE QUESTIONS

16.93 Monensin, a complex antibiotic produced by the bacterium *Streptomyces cinamonsis,* is added to cattle feed to protect the cattle from infection. Identify each oxygen-containing functional group.



monensin

16.94 Chloral hydrate is a sedative formed by the addition of water to chloral (Cl_3CCHO). Chloral hydrate is sometimes used to calm a patient prior to a surgical procedure. It has also been used for less reputable purposes. Adding it to an alcoholic beverage forms a so-called "knock-out drink," causing an individual to pass out. Although we have not studied the formation of hydrates from aldehydes, this reaction resembles the addition of alcohols to aldehydes to form hemiacetals. What is the structure of chloral hydrate?

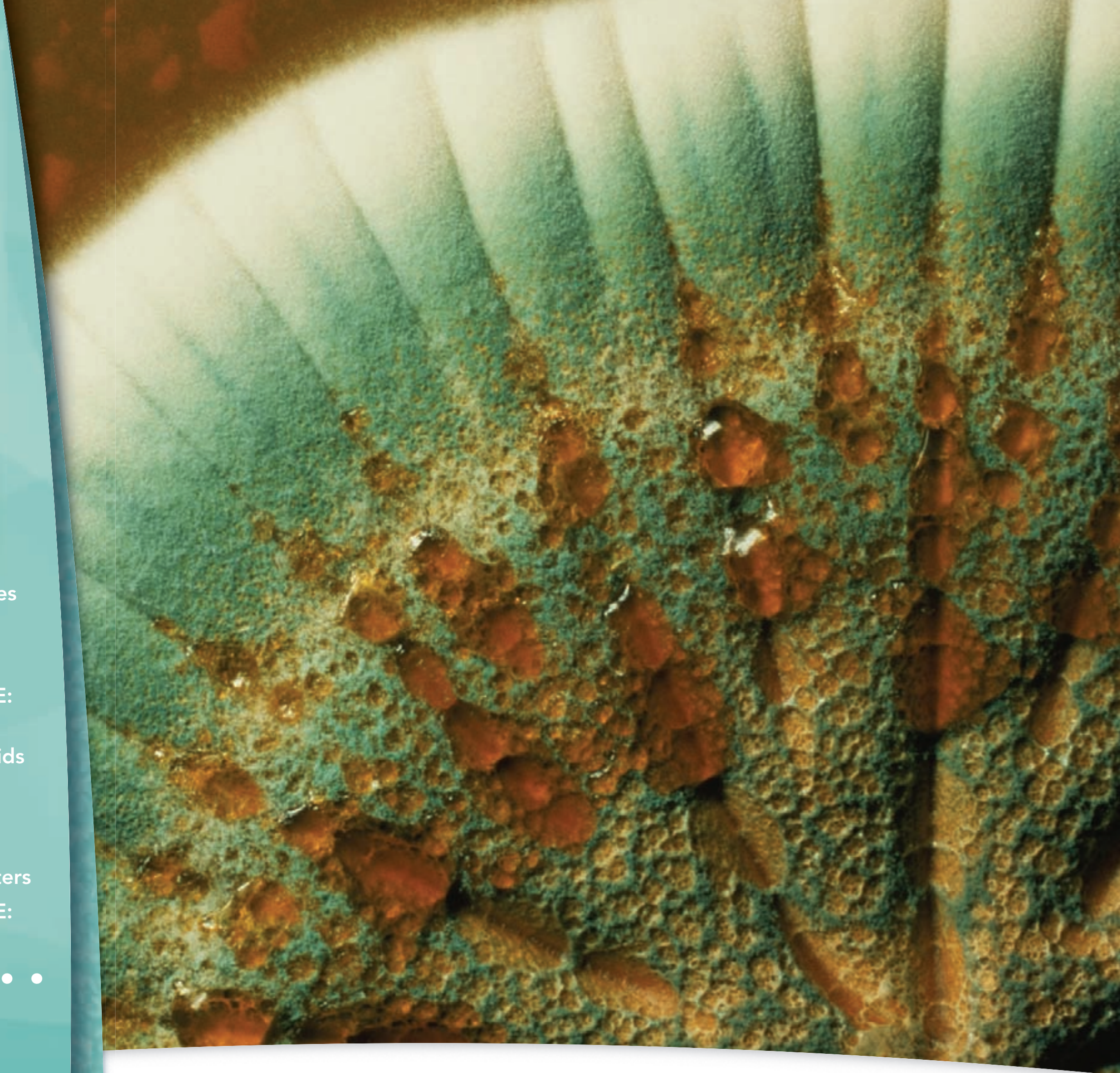
17

CHAPTER OUTLINE

CHAPTER GOALS

In this chapter you will learn how to:

1. Identify the characteristics of carboxylic acids, esters, and amides
2. Name carboxylic acids, esters, and amides
3. Give examples of useful carboxylic acids
4. Give examples of useful esters and amides
5. Draw the products of acid–base reactions of carboxylic acids
6. Explain how soap cleans away dirt
7. Discuss the acid–base chemistry of aspirin
8. Convert carboxylic acids to esters and amides
9. Draw the products of the hydrolysis of esters and amides
10. Draw the structures of polyesters and polyamides
11. Explain how penicillin works



Penicillin, an amide discovered by Scottish bacteriologist Sir Alexander Fleming in 1928, is an antibiotic produced by the mold *Penicillium notatum.*

CARBOXYLIC ACIDS, ESTERS, AND AMIDES

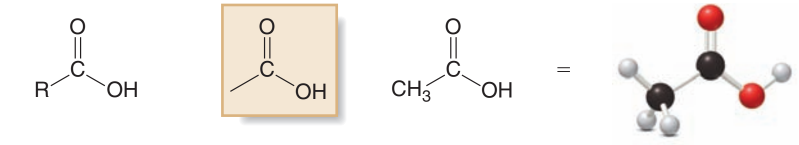
CHAPTER 17 is the second of two chapters that concentrates on compounds that contain a **carbonyl group (C=O).** While Chapter 16 focused on aldehydes (RCHO) and ketones (R_2CO), Chapter 17 discusses the chemistry and properties of **carboxylic acids (RCOOH), esters (RCOOR'), and amides ($RCONR'_2$).** All three families of organic compounds occur widely in nature, and many useful synthetic compounds have been prepared as well. Simple carboxylic acids like acetic acid (CH_3COOH) have a sour taste and a biting odor, and long-chain carboxylic acids form vegetable oils and animal fat. Simple esters have easily recognized fragrances, and the most abundant lipids contain three ester groups. Several useful drugs are amides, and all proteins, such as those that form hair, muscle, and connective tissue, contain many amide units.

17.1 STRUCTURE AND BONDING

Carboxylic acids, esters, and **amides** are three families of organic molecules that contain a **carbonyl group (C═O)** bonded to an element more electronegative than carbon.

- *Carboxylic acids* are organic compounds containing a carboxyl group (COOH).

General structure



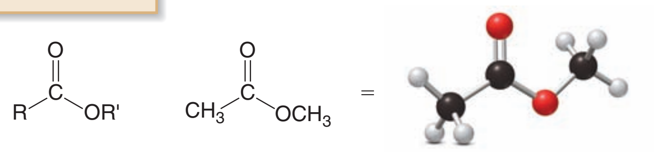
carboxylic acid — **carboxyl group** — acetic acid — CH_3CO_2H

The word **carboxyl** (for a COOH group) is derived from ***carb***onyl (C═O) + hydr***oxyl*** (OH).

Although the structure of a carboxylic acid is often abbreviated as **RCOOH** or **RCO_2H,** keep in mind that the central carbon atom of the functional group has a double bond to one oxygen atom and a single bond to another.

- *Esters* are carbonyl compounds that contain an alkoxy group (OR') bonded to the carbonyl carbon.

General structure



ester — methyl acetate — $CH_3CO_2CH_3$

The structure of an ester is often abbreviated as RCOOR' or RCO_2R'.

- *Amides* are carbonyl compounds that contain a nitrogen atom bonded to the carbonyl carbon.

General structure

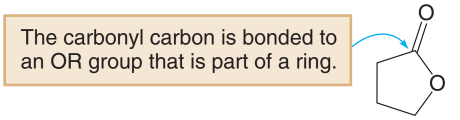


amide, R' = H or alkyl — **1°** amide, 1 C—N bond — **2°** amide, 2 C—N bonds — **3°** amide, 3 C—N bonds

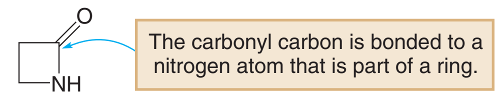
The N atom of an amide may be bonded to other hydrogen atoms or alkyl groups. Amides are classified as **1°, 2°,** or **3°** depending on the number of carbon atoms bonded directly to the *nitrogen* atom.

- A primary (1°) amide contains one C—N bond. A 1° amide has the structure $RCONH_2$.
- A secondary (2°) amide contains two C—N bonds. A 2° amide has the structure RCONHR'.
- A tertiary (3°) amide contains three C—N bonds. A 3° amide has the structure $RCONR'_2$.

Cyclic esters and amides are known. **A cyclic ester is called a *lactone.* A cyclic amide is called a *lactam.***

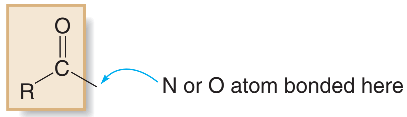


cyclic ester
lactone



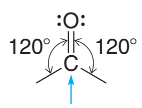
cyclic amide
lactam

Carboxylic acids, esters, and amides are called **acyl compounds,** since they contain an **acyl group (RCO)** bonded to an electronegative atom.

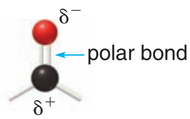


acyl group

The two most important features of acyl compounds, like other carbonyl compounds, are the following:

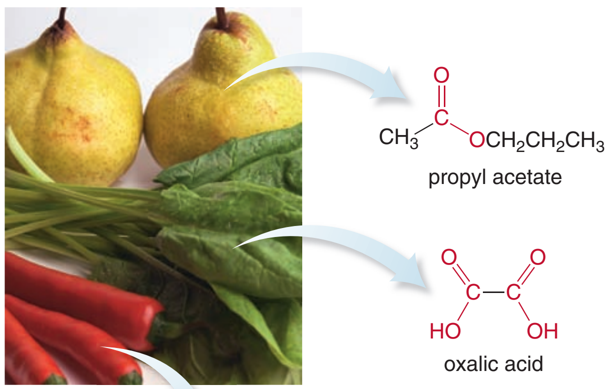


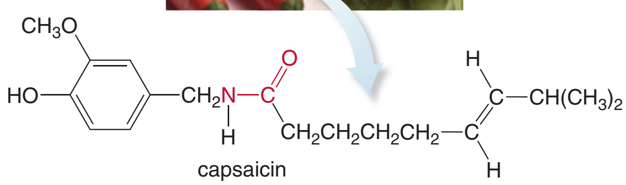
trigonal planar



- **The carbonyl carbon is trigonal planar, so all bond angles are 120°.**
- **The electronegative oxygen atom makes the carbonyl group polar, so the carbonyl carbon is electron poor (δ^+) and the carbonyl oxygen is electron rich (δ^-).**

Oxalic acid (a carboxylic acid) in spinach, propyl acetate (an ester) in pears, and capsaicin (an amide) in hot peppers are examples of acyl compounds.





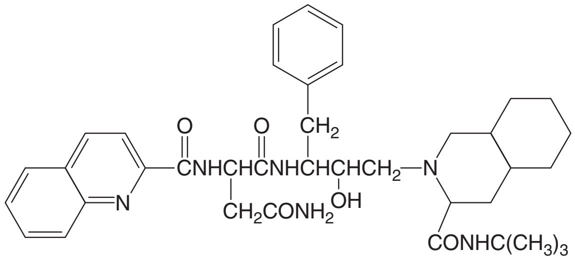
capsaicin

PROBLEM 17.1 Draw out each compound to clearly show what groups are bonded to the carbonyl carbon. Label each compound as a carboxylic acid, ester, or amide.

a. $CH_3CH_2CO_2CH_2CH_3$ b. $CH_3CONHCH_3$ c. $(CH_3)_3CCO_2H$ d. $(CH_3)_2CHCON(CH_3)_2$

PROBLEM 17.2

Invirase is the trade name for saquinavir, a drug used to treat HIV. Classify each amide in Invirase as 1°, 2°, or 3°.



saquinavir
(Trade name: Invirase)

17.2 NOMENCLATURE

To name carboxylic acids, esters, and amides, we must learn the suffix that identifies each functional group in the IUPAC system. Since the names of esters and amides are derived from carboxylic acids, we must first learn how to name carboxylic acids. With esters, 2° amides, and 3° amides, the name of the acyl compound has two distinct portions: an acyl group that contains the carbonyl, and one or two alkyl groups bonded to the oxygen or nitrogen atom.

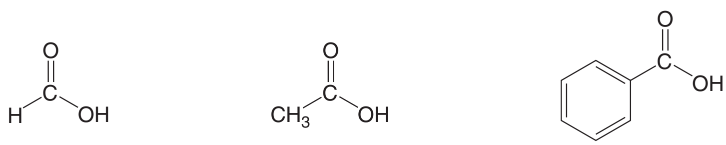
17.2A NAMING A CARBOXYLIC ACID—RCOOH

- **In the IUPAC system, carboxylic acids are identified by the suffix *-oic acid.***

To name a carboxylic acid using the IUPAC system:

1. **Find the longest chain containing the COOH group, and change the *-e* ending of the parent alkane to the suffix *-oic acid.***
2. **Number the carbon chain to put the COOH group at C1, but omit this number from the name. Apply all of the other usual rules of nomenclature.**

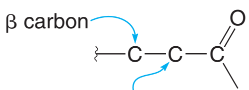
Many simple carboxylic acids are often referred to by their common names. A common name uses the suffix ***-ic acid.*** Three common names are virtually always used.



formic acid (methanoic acid) — acetic acid (ethanoic acid) — benzoic acid (benzenecarboxylic acid)

[IUPAC names are given in parentheses, and are rarely used.]

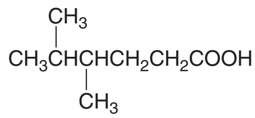
Greek letters are sometimes used to designate the carbons near carbonyl groups. These terms can be used for any carbonyl group.



- **The carbon adjacent to the COOH is called the α (alpha) carbon.**
- **The carbon bonded to the α carbon is the β (beta) carbon.**

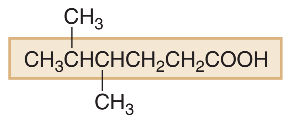
SAMPLE PROBLEM 17.1

Give the IUPAC name of the following carboxylic acid.



ANALYSIS AND SOLUTION

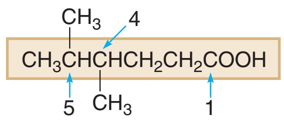
[1] Find and name the longest chain containing COOH.



hexane - - - → hexan*oic acid*
(6 C's)

The COOH contributes one C to the longest chain.

[2] Number and name the substituents, making sure the COOH group is at C1.

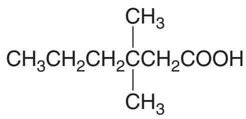


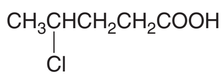
two methyl substituents on C4 and C5

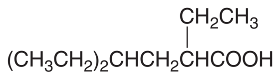
Answer: 4,5-dimethylhexanoic acid

PROBLEM 17.3

Give the IUPAC name for each compound.

a. 

b. 

c. 

PROBLEM 17.4

Give the structure corresponding to each IUPAC name.

a. 2-bromobutanoic acid
b. 2,3-dimethylpentanoic acid
c. 2-ethyl-5,5-dimethyloctanoic acid
d. 3,4,5,6-tetraethyldecanoic acid

17.2B NAMING AN ESTER—RCOOR'

The names of esters are derived from the names of the parent carboxylic acids. Keep in mind that the common names **formic acid, acetic acid,** and **benzoic acid** are used for the parent acid, so these common parent names are used for their derivatives as well.

An ester has two parts to its structure, each of which must be named separately: an **acyl group** that contains the carbonyl group (**RCO—**) and an **alkyl group** (designated as **R'**) bonded to the oxygen atom.

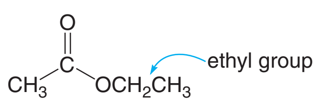
- **In the IUPAC system, esters are identified by the suffix *-ate.***

HOW TO Name an Ester (RCO_2R') Using the IUPAC System

EXAMPLE **Give a systematic name for the ester $CH_3CO_2CH_2CH_3$.**

Step [1] **Name the R' group bonded to the oxygen atom as an alkyl group.**

- The name of the alkyl group, ending in the suffix *-yl*, becomes the *first* part of the ester name. In this case, a two-carbon *ethyl* group is bonded to the ester oxygen atom.



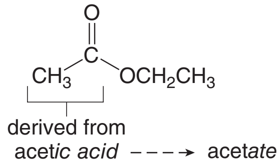
(Continued)

How To, continued...

Step [2] Name the acyl group (RCO–) by changing the *-ic acid* ending of the parent carboxylic acid to the suffix *-ate*.

- The name of the acyl group becomes the *second* part of the name.
- In this case, the name of the parent two-carbon carboxylic acid, acet*ic acid*, becomes acet*ate*.

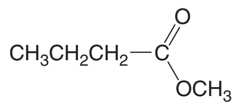
Esters are often written as RCOOR', where the alkyl group (R') is written *last.* When an ester is named, however, the R' group appears *first* in the name.



Answer: ethyl acetate

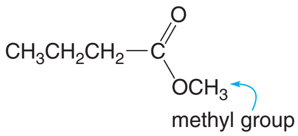
SAMPLE PROBLEM 17.2

Give the IUPAC name of the following ester, which occurs naturally in apples.



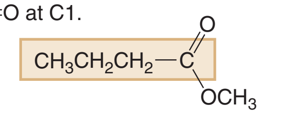
ANALYSIS AND SOLUTION

[1] Name the alkyl group on the O atom.



The word *methyl* becomes the first part of the name.

[2] To name the acyl group, find and name the longest chain containing the carbonyl group, placing the C═O at C1.



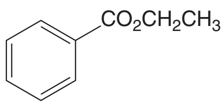
butano*ic acid* ---→ butano*ate*
(4 C's)

Answer: methyl butanoate

PROBLEM 17.5

Give an acceptable name for each ester.

a. $CH_3(CH_2)_4CO_2CH_3$

b. 

c. $CH_3CH_2CH_2CH_2COOCH_2CH_2CH_3$

PROBLEM 17.6

Give the structure corresponding to each name.

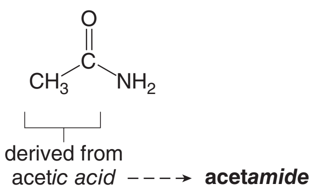
a. propyl propanoate
b. butyl acetate
c. ethyl hexanoate
d. methyl benzoate

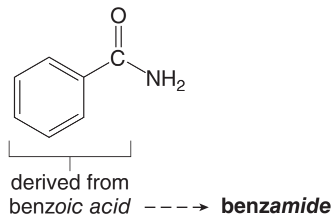
17.2C NAMING AN AMIDE

- **In the IUPAC system, amides are identified by the suffix *-amide.***

All 1° amides are named by replacing the ***-oic acid*** ending (or *-ic acid* ending of a common name) with the suffix ***-amide.***

Naming 1° amides

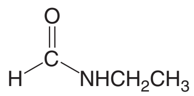


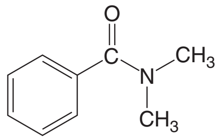


A 2° or 3° amide has two parts to its structure: an **acyl group** that contains the carbonyl group (**RCO–**) and one or two **alkyl groups** bonded to the nitrogen atom.

HOW TO Name a 2° or 3° Amide

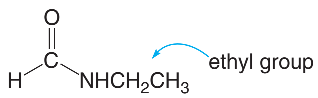
EXAMPLE **Give a systematic name for each amide.**

a. 

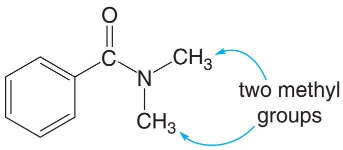
b. 

Step [1] **Name the alkyl group (or groups) bonded to the N atom of the amide. Use the prefix "*N*-" preceding the name of each alkyl group.**

- The name of the alkyl groups forms the first part of each amide name.
- For 3° amides, use the prefix **di-** if the two alkyl groups on N are the same. If the two alkyl groups are different, **alphabetize** their names. One "***N*-**" is needed for each alkyl group, even if both R groups are identical.

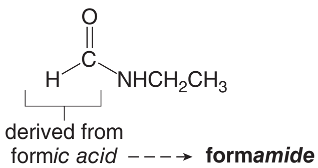
a. 

- The compound is a 2° amide with one ethyl group → *N*-ethyl.

b. 

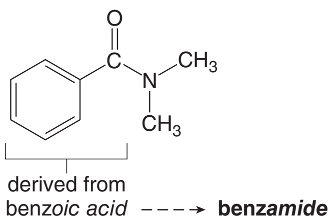
- The compound is a 3° amide with two methyl groups.
- Use the prefix di- and two "*N*-" to begin the name → *N,N*-dimethyl.

Step [2] **Name the acyl group (RCO–) with the suffix *-amide.***

a. 

- Change the *-ic acid* or *-oic acid* suffix of the parent carboxylic acid to the suffix *-amide*.
- Put the two parts of the name together.

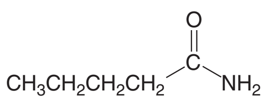
Answer: *N*-ethylformamide

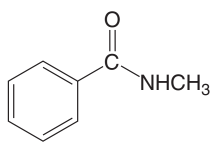
b. 

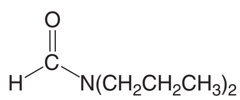
- Change benz*oic acid* to benz*amide*.
- Put the two parts of the name together.

Answer: *N,N*-dimethylbenzamide

PROBLEM 17.7 Give an acceptable name for each amide.

a. 

b. 

c. 

PROBLEM 17.8 Draw the structure of each amide.

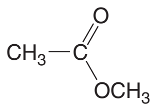
a. propanamide
b. *N*-ethylhexanamide
c. *N,N*-dimethylacetamide
d. *N*-butyl-*N*-methylbutanamide

17.3 PHYSICAL PROPERTIES

Carboxylic acids, esters, and amides are polar compounds because they possess a polar carbonyl group. All C—O, O—H, C—N, and N—H bonds in these compounds are polar bonds as well, and thus contribute to the net dipole of each compound.

Carboxylic acids also exhibit intermolecular **hydrogen bonding** since they possess a hydrogen atom bonded to an electronegative oxygen atom. Carboxylic acids often exist as **dimers,** held together by *two* intermolecular hydrogen bonds, as shown in Figure 17.1. The carbonyl oxygen atom of one molecule hydrogen bonds to the hydrogen atom of another molecule. As a result:

- **Carboxylic acids have stronger intermolecular forces than esters, giving them higher boiling points and melting points, when comparing compounds of similar size.**



bp 58 °C

no hydrogen bonding possible



bp 141 °C

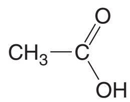
stronger intermolecular forces
higher boiling point

Carboxylic acids also have stronger intermolecular forces than alcohols, even though both functional groups exhibit hydrogen bonding; two molecules of a carboxylic acid are held together by *two* intermolecular hydrogen bonds, whereas only *one* hydrogen bond is possible between two molecules of an alcohol (Section 14.2). As a result:

- **Carboxylic acids have higher boiling points and melting points than alcohols of comparable size.**

$CH_3CH_2CH_2OH$

1-propanol
bp 97 °C



acetic acid
bp 118 °C

more hydrogen-bonding interactions possible
higher boiling point

FIGURE 17.1 Two Molecules of Acetic Acid (CH_3COOH) Held Together by Two Hydrogen Bonds

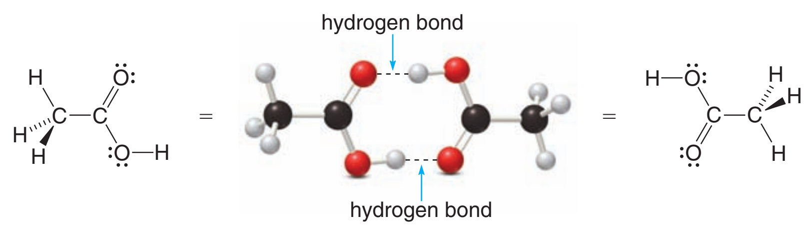
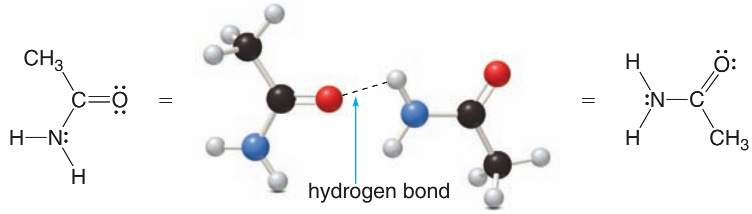
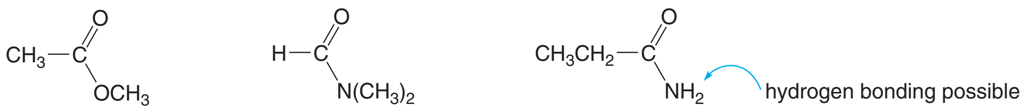


FIGURE 17.2 Intermolecular Hydrogen Bonding Between Two CH_3CONH_2 Molecules



Primary (1°) and 2° amides contain N—H bonds, so hydrogen bonding is possible between two molecules of the amide, as shown in Figure 17.2. This gives 1° and 2° amides stronger intermolecular forces than 3° amides and esters, which can't intermolecularly hydrogen bond. As a result:

- **Primary (1°) and 2° amides have higher boiling points and melting points than esters and 3° amides of comparable size.**



ester	3° amide	1° amide
bp 58 °C	bp 153 °C	bp 213 °C

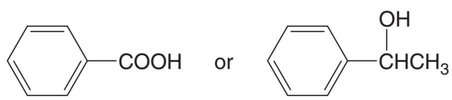
strongest intermolecular forces
highest boiling point

Like other oxygen-containing compounds, carboxylic acids, esters, and amides having less than six carbons are soluble in water. Higher molecular weight acyl compounds are insoluble in water because the nonpolar portion of the molecule, the C—C and C—H bonds, gets larger than the polar carbonyl group.

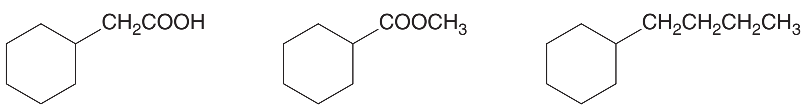
PROBLEM 17.9 Which compound in each pair has the higher boiling point?

a. CH_3COOH or CH_3CH_2CHO

b. $CH_3CH_2CH_2CONH_2$ or $CH_3CH_2CO_2CH_3$

c. 

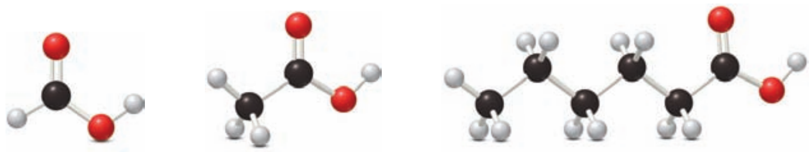
PROBLEM 17.10 Rank the following compounds in order of increasing boiling point. Which compound is the most water soluble? Which compound is the least water soluble?



PROBLEM 17.11 Why is the boiling point of CH_3CONH_2 (221 °C) higher than the boiling point of $CH_3CON(CH_3)_2$ (166 °C), even though the latter compound has a higher molecular weight and more surface area?

17.4 INTERESTING CARBOXYLIC ACIDS IN CONSUMER PRODUCTS AND MEDICINES

Simple carboxylic acids have biting or foul odors.



HCO_2H CH_3CO_2H $CH_3CH_2CH_2CH_2CH_2CO_2H$

- **Formic acid** (HCO_2H) is responsible for the sting of some types of ants.
- **Acetic acid** (CH_3CO_2H) is the sour-tasting component of vinegar. Air oxidation of ethanol (CH_3CH_2OH) to acetic acid makes "bad" wine taste sour.
- **Hexanoic acid** [$(CH_3(CH_2)_4COOH$] has the foul odor associated with dirty socks and locker rooms. It also contributes to the unpleasant odor of ginkgo seeds. The common name for hexanoic acid is caproic acid, derived from the Latin word caper, meaning "goat."

HEALTH NOTE

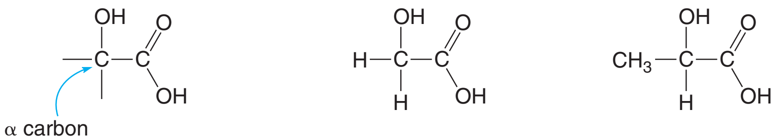


Ginkgo trees have existed for over 280 million years. Extracts of the ginkgo tree have long been used in China, Japan, and India in medicine and cooking.

17.4A FOCUS ON HEALTH & MEDICINE SKIN CARE PRODUCTS

Several skin care products that purportedly smooth fine lines and improve skin texture contain α-hydroxy acids. **α-Hydroxy acids contain a hydroxyl group on the α (alpha) carbon to the carboxyl group.** Two common α-hydroxy acids are glycolic acid and lactic acid. Glycolic acid occurs naturally in sugarcane, and lactic acid gives sour milk its distinctive taste.

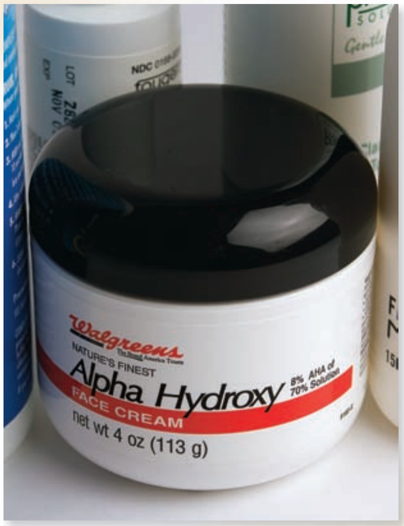
General structure



α-hydroxy acid glycolic acid lactic acid

Do products that contain α-hydroxy acids make the skin look younger? α-Hydroxy acids react with the outer layer of skin cells, causing them to loosen and flake off. Underneath is a layer of healthier looking skin that has not been exposed to the sun. In this way, these skin products do not actually reverse the aging process; rather, they remove a layer of old skin that may be less pliant or contain small age spots. They can, however, give the appearance of younger skin for a time.

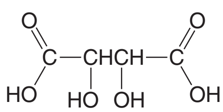
CONSUMER NOTE



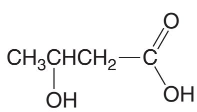
α-Hydroxy acids are used in skin care products that are promoted to remove wrinkles and age spots.

PROBLEM 17.12 Label the chirality center in lactic acid. Draw both enantiomers of lactic acid (Section 15.3).

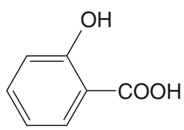
PROBLEM 17.13 Which compounds are α-hydroxy acids?

a. 

tartaric acid
(isolated from grapes)

b. 

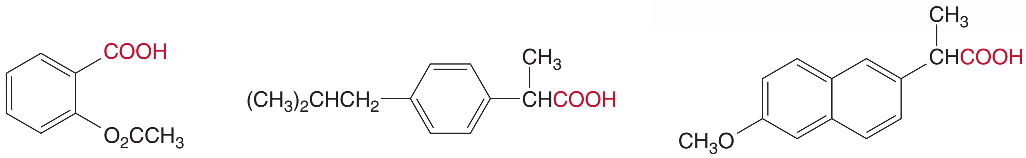
3-hydroxybutanoic acid
(starting material for
polymer synthesis)

c. 

salicylic acid
(isolated from meadowsweet)

17.4B FOCUS ON HEALTH & MEDICINE ASPIRIN AND ANTI-INFLAMMATORY AGENTS

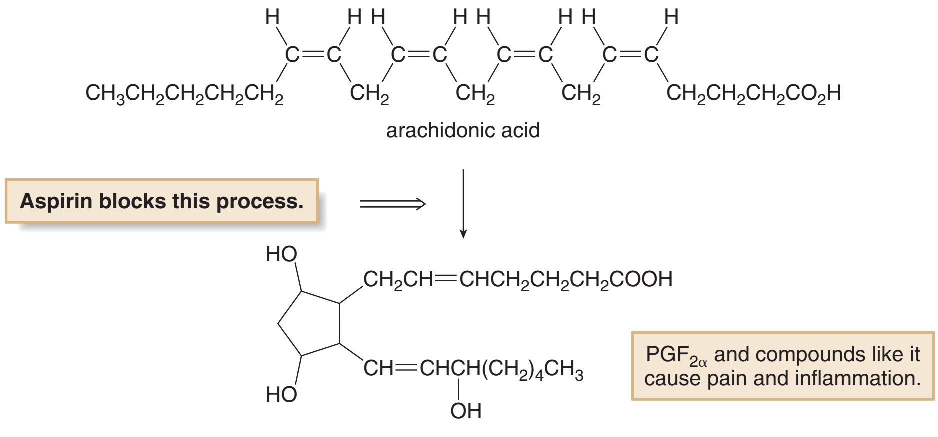
Three common pain relievers that are also anti-inflammatory agents contain a carboxyl group—aspirin, ibuprofen, and naproxen.



aspirin ibuprofen naproxen

How does aspirin relieve pain and reduce inflammation? Although aspirin is the most widely used pain reliever and anti-inflammatory agent and has been sold since the late 1800s, its mechanism of action remained unknown until the 1970s. At that time it was shown that aspirin blocks the synthesis of **prostaglandins,** carboxylic acids containing 20 carbons that are responsible for mediating pain, inflammation, and a wide variety of other biological functions.

Prostaglandins are not stored in cells. Rather, they are synthesized on an as-needed basis from arachidonic acid, an unsaturated fatty acid with four cis double bonds. **Aspirin relieves pain and decreases inflammation because it prevents the synthesis of prostaglandins, the compounds responsible for both of these physiological responses, from arachidonic acid.**



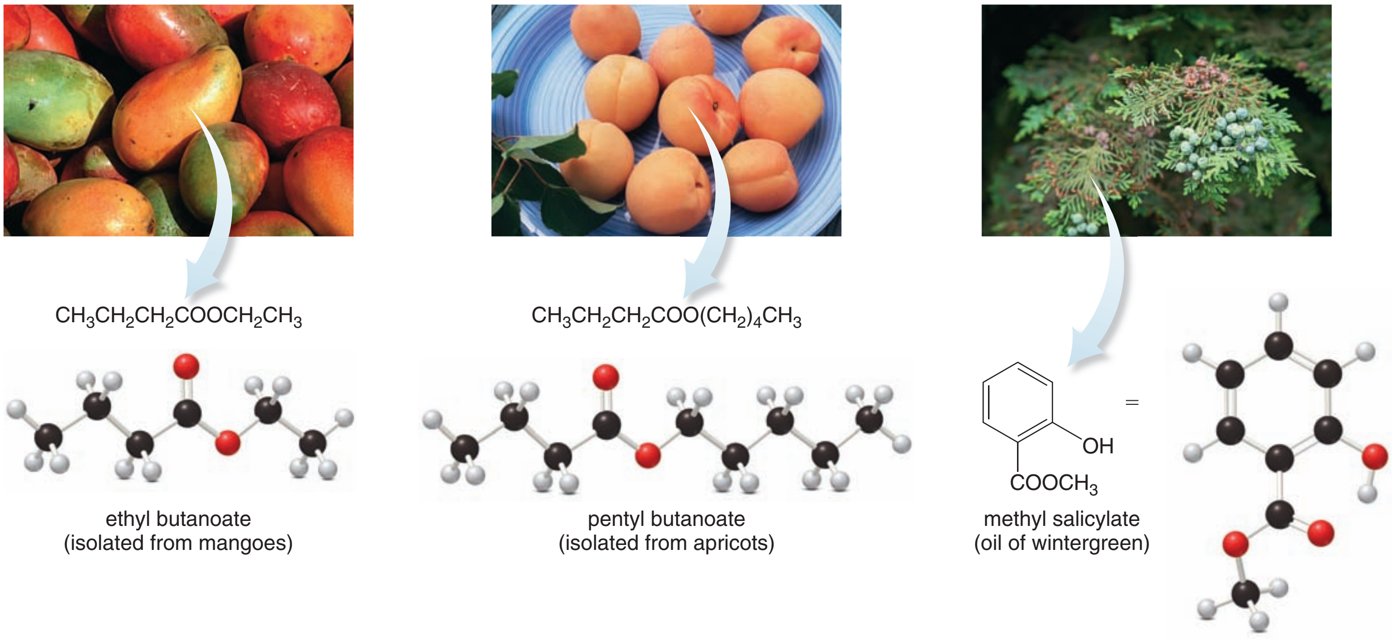
$PGF_{2\alpha}$
a prostaglandin

The 1982 Nobel Prize in Physiology or Medicine was awarded to John Vane, Bengt Samuelsson, and Sune Bergstrom for unraveling the details of prostaglandin synthesis, thus showing how aspirin acts.

PROBLEM 17.14 Which compound, $PGF_{2\alpha}$ (a prostaglandin) or arachidonic acid, is more water soluble? Explain your choice.

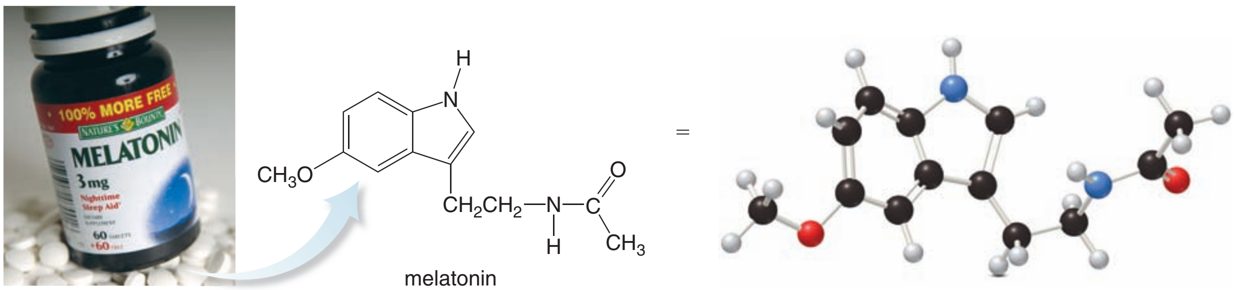
17.5 INTERESTING ESTERS AND AMIDES

Many low molecular weight esters have pleasant and very characteristic odors. These include ethyl butanoate (from mangoes), pentyl butanoate (from apricots), and methyl salicylate (oil of wintergreen).



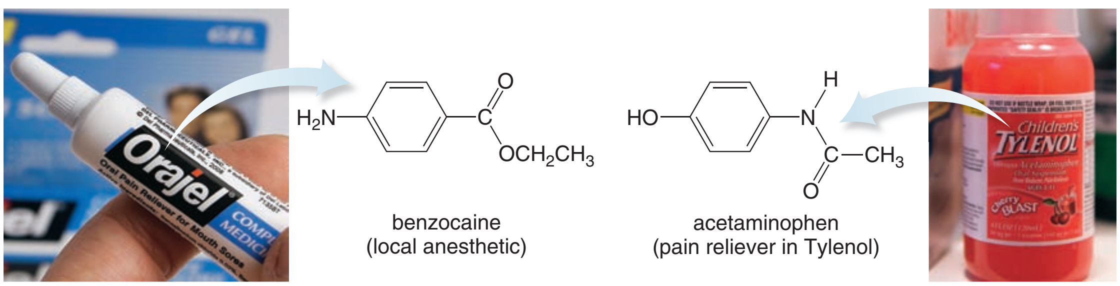
Esters are a common functional group in many lipids, as we will learn in Section 17.9 and Chapter 19.

Melatonin, an amide synthesized by the brain's pineal gland, is thought to induce sleep. Melatonin levels in the body rise as less light falls upon the eye and drop quickly at dawn. For this reason, melatonin has become a popular supplement for travelers suffering from jet lag and individuals with mild sleep disorders.



We will learn about proteins, naturally occurring polyamides, in Chapter 21.

Many useful drugs are esters or amides. **Benzocaine,** an ester, is the active ingredient in many over-the-counter oral topical anesthetics such as Orajel. **Acetaminophen,** an amide, is the active ingredient in Tylenol. Acetaminophen relieves pain and fever. In large doses acetaminophen causes liver damage, so dosage recommendations must be carefully followed.

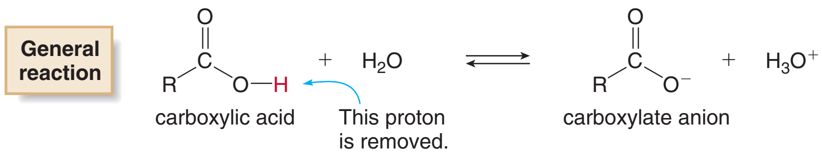


PROBLEM 17.15 Exaltolide is a synthetic lactone with a musky odor used in perfumes. Exaltolide has molecular formula $C_{14}H_{26}O_2$ and contains a 15-membered ring. Draw its structure.

PROBLEM 17.16 In addition to ethyl butanoate (Section 17.5), mangoes contain several other esters. Draw the structure of each of the following esters that has been isolated from the mango: (a) butyl formate; (b) ethyl octanoate; (c) ethyl propanoate.

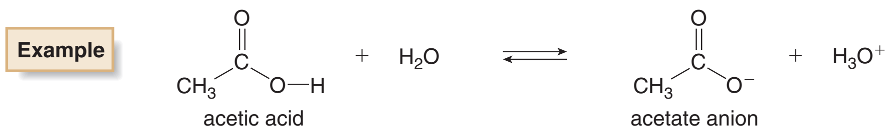
17.6 THE ACIDITY OF CARBOXYLIC ACIDS

As their name implies, **carboxylic acids are acids;** that is, **they are *proton donors.*** When a carboxylic acid is dissolved in water, an acid–base equilibrium occurs: the carboxylic acid donates a proton to H_2O, forming its conjugate base, a **carboxylate anion,** and water gains a proton, forming its conjugate acid, H_3O^+.



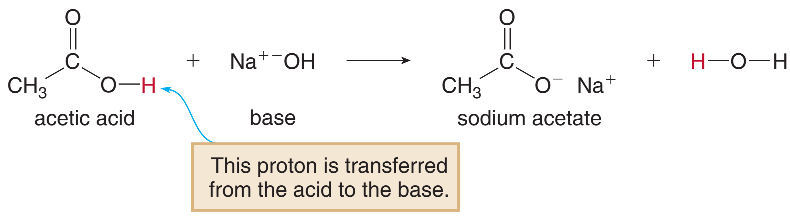
K_a values for a variety of acids are given in Section 9.4.

While carboxylic acids are more acidic than other families of organic compounds, they are weak acids compared to inorganic acids like HCl or H_2SO_4. Typical acid dissociation constants (K_a) for carboxylic acids fall in the range 10^{-4} to 10^{-5}. Thus, only a small percentage of a carboxylic acid is ionized in aqueous solution.



17.6A REACTION WITH BASES

Carboxylic acids react with bases such as NaOH to form water-soluble salts. In this reaction, the acid–base equilibrium is shifted to the right, and essentially all of the carboxylic acid is converted to its carboxylate anion.



- **A proton is removed from acetic acid (CH_3COOH) to form its conjugate base, the acetate anion (CH_3COO^-), which is present in solution as its sodium salt, sodium acetate.**
- **Hydroxide (^-OH) gains a proton to form neutral H_2O.**

Similar acid–base reactions occur with other hydroxide bases (KOH), sodium bicarbonate ($NaHCO_3$), and sodium carbonate (Na_2CO_3). **In each reaction, a proton is transferred from the acid (RCOOH) to the base.**

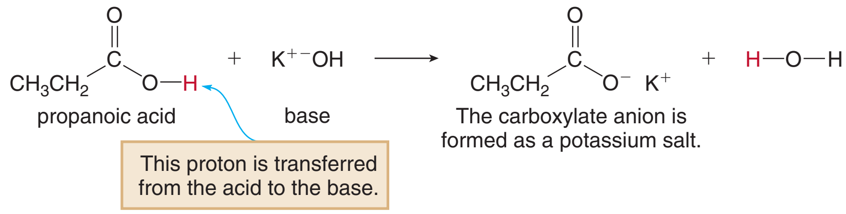
SAMPLE PROBLEM 17.3

What products are formed when propanoic acid (CH_3CH_2COOH) reacts with potassium hydroxide (KOH)?

ANALYSIS In any acid–base reaction with a carboxylic acid:

- Remove a proton from the carboxyl group (COOH) and form the carboxylate anion ($RCOO^-$).
- Add a proton to the base. If the base has a –1 charge to begin with, it becomes a neutral product when a proton (H^+) is added to it.
- Balance the charge of the carboxylate anion by drawing it as a salt with a metal cation.

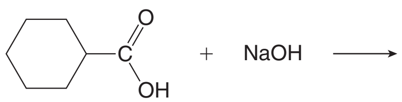
SOLUTION

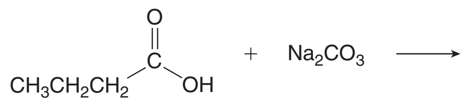


Thus, CH_3CH_2COOH loses a proton to form $CH_3CH_2COO^-$, which is present in solution as its potassium salt, $CH_3CH_2COO^- K^+$. Hydroxide (^-OH) gains a proton to form H_2O.

PROBLEM 17.17

Draw the products of each acid–base reaction.

a. 

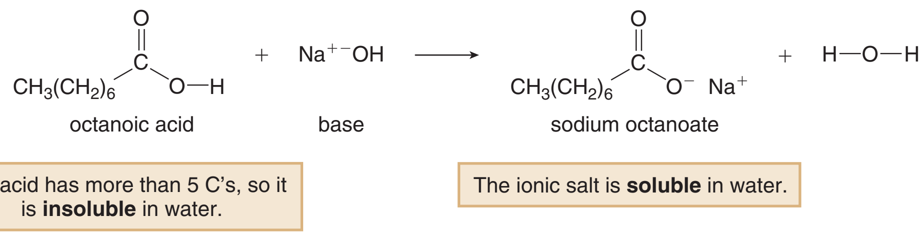
b. 

PROBLEM 17.18

What products are formed when benzoic acid (C_6H_5COOH) is treated with each base: (a) NaOH; (b) Na_2CO_3; (c) $NaHCO_3$?

17.6B CARBOXYLATE ANIONS—SALTS OF CARBOXYLIC ACIDS

The salts of carboxylic acids that are formed by acid–base reactions are water-soluble ionic solids. Thus, a water-*insoluble* carboxylic acid like octanoic acid can be converted to its water-*soluble* sodium salt by reaction with NaOH. This reaction is important in determining the solubility of drugs that contain a carboxyl group, as we will learn in Section 17.7.

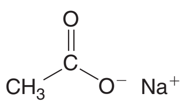


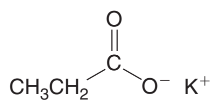
To name the metal salts of carboxylate anions, three parts must be put together: the name of the metal cation, the parent name indicating the number of carbons in the parent carboxylic acid, and the suffix indicating that the species is a salt. The suffix is added by changing the ***-ic acid*** ending of the parent carboxylic acid to the suffix ***-ate***.

name of the metal cation + **parent** + ***-ate* (suffix)**

SAMPLE PROBLEM 17.4

Give an acceptable name for each salt.

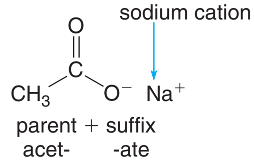
a. 

b. 

ANALYSIS Name the carboxylate salt by putting three parts together:

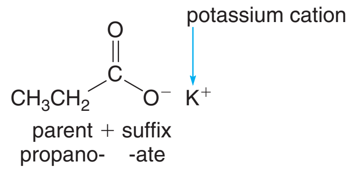
- the name of the metal cation
- the parent name that indicates the number of carbons in the parent chain
- the suffix, *-ate*

SOLUTION

a. 

- The first part of the name is the metal cation, sodium.
- The parent name is derived from the common name, acetic acid. Change the ***-ic acid*** ending to ***-ate***; acetic acid → acetate.

Answer: sodium acetate

b. 

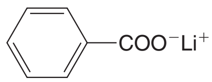
- The first part of the name is the metal cation, potassium.
- The parent name is derived from the IUPAC name, propanoic acid. Change the ***-ic acid*** ending to ***-ate***; propanoic acid → propanoate.

Answer: potassium propanoate

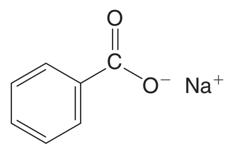
PROBLEM 17.19

Name each salt of a carboxylic acid.

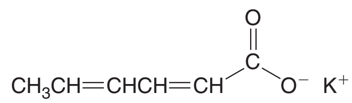
a. $CH_3CH_2CH_2CO_2^{-}Na^{+}$

b. 

Salts of carboxylic acids are commonly used as preservatives. **Sodium benzoate,** which inhibits the growth of fungus, is a preservative used in soft drinks, and potassium sorbate is an additive that prolongs the shelf-life of baked goods and other foods. These salts do not kill bacteria or fungus. They increase the pH of the product, thus preventing further growth of microorganisms.



sodium benzoate



potassium sorbate

PROBLEM 17.20

Draw the structure of sodium propanoate, a common preservative.

17.6C HOW DOES SOAP CLEAN AWAY DIRT?

Soap has been used by humankind for some 2,000 years. Historical records describe its manufacture in the first century and document the presence of a soap factory in Pompeii. Prior to this time, clothes were cleaned by rubbing them on rocks in water, or by forming soapy lathers from the roots, bark, and leaves of certain plants. These plants produced natural materials called *saponins,* which act in much the same way as modern-day soaps.

Soaps are salts of carboxylic acids that have many carbon atoms in a long hydrocarbon chain. A soap molecule has two parts.

- The ionic end is called the *polar head.*
- The carbon chain of nonpolar C—C and C—H bonds is called the *nonpolar tail.*

Structure of a soap molecule

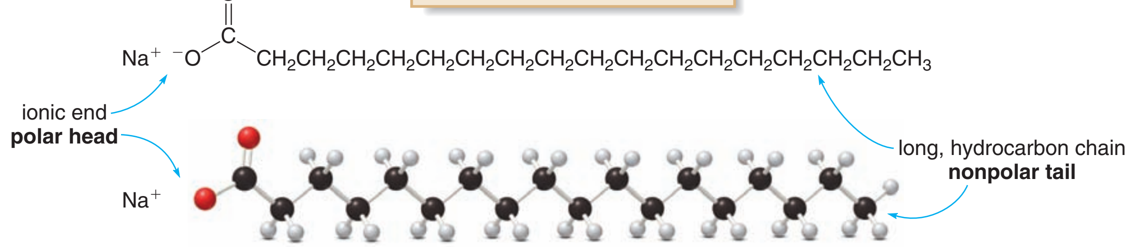
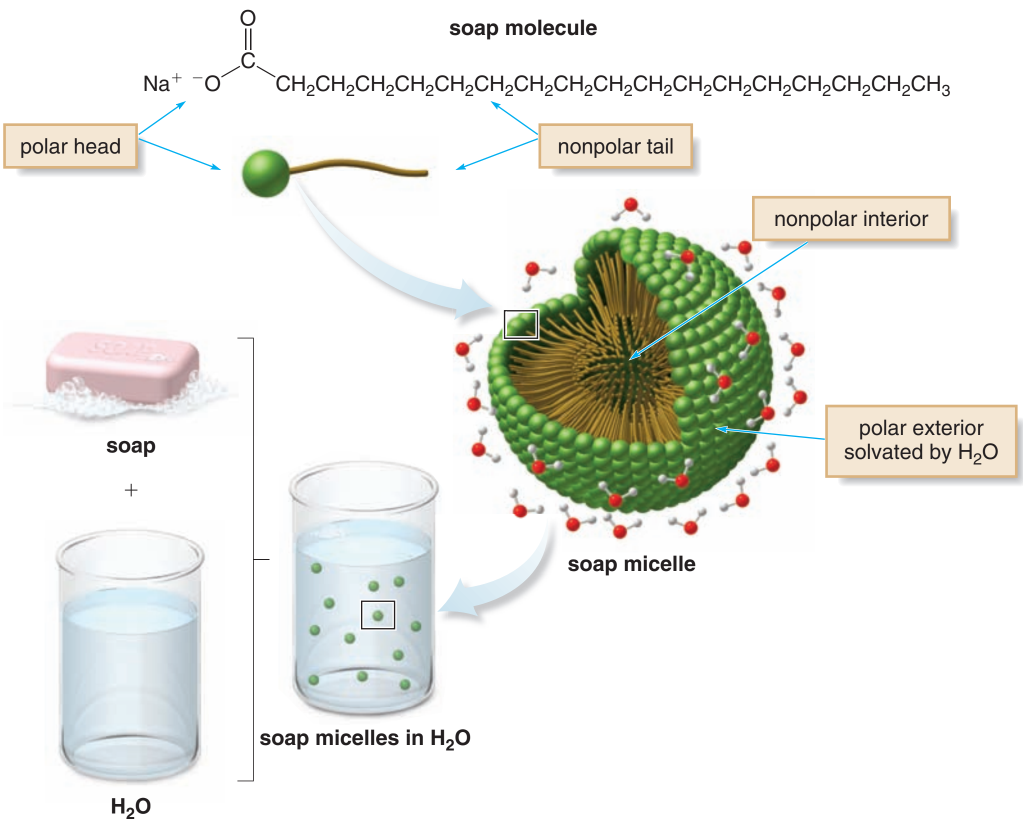


FIGURE 17.3 Dissolving Soap in Water



When soap is dissolved in H_2O, the molecules form spherical droplets with the nonpolar tails in the interior and the polar heads on the surface.

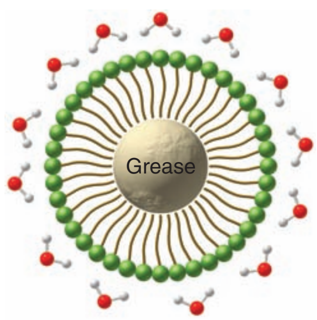
Dissolving soap in water forms **spherical droplets having the ionic heads on the surface and the nonpolar tails packed together in the interior.** These spherical droplets are called ***micelles*** and are illustrated in Figure 17.3. In this arrangement, the ionic heads can interact with the polar solvent water, and this brings the nonpolar, "greasy" hydrocarbon portion of the soap into solution.

How does soap dissolve grease and oil? The polar solvent water alone cannot dissolve dirt, which is composed largely of nonpolar hydrocarbons. When soap is mixed with water, however, the nonpolar hydrocarbon tails dissolve the dirt in the interior of the micelle. The polar head of the soap remains on the surface to interact with water. The nonpolar tails of the soap molecules are so well sealed off from the water by the polar head groups that the micelles are water soluble, so they can separate from the fibers of our clothes and be washed down the drain with water. In this way, soaps do a seemingly impossible task: they remove nonpolar hydrocarbon material from skin and clothes by dissolving it in the polar solvent water.

CONSUMER NOTE

All soaps are metal salts of carboxylate anions. The main difference between brands is the addition of other ingredients that do not alter their cleaning properties: dyes for color, scents for a pleasing odor, and oils for lubrication. Soaps that float have been aerated so that they are less dense than water.

Cross-section of a soap micelle with a grease particle dissolved in the interior



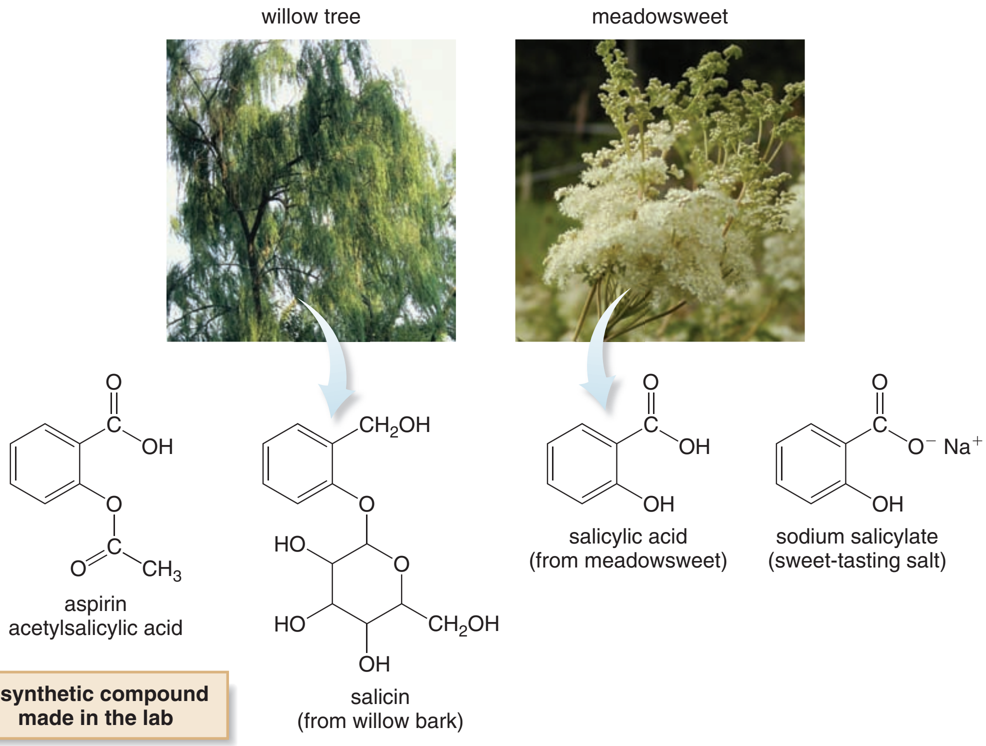
PROBLEM 17.21 Draw the structure of a soap molecule that has a potassium cation and a carboxylate anion containing 16 carbons.

17.7 FOCUS ON HEALTH & MEDICINE ASPIRIN

Aspirin is one of the most widely used over-the-counter drugs. Whether you purchase Anacin, Bufferin, Bayer, or a generic, the active ingredient is the same—**acetylsalicylic acid.** Aspirin is a synthetic compound; that is, it does not occur in nature, but it is similar in structure to salicin found in willow bark and salicylic acid found in meadowsweet blossoms.

The modern history of aspirin dates back to 1763 when Reverend Edmund Stone reported on the analgesic effects of chewing on the bark of the willow tree. Willow bark is now known to contain salicin, which is structurally similar to aspirin.

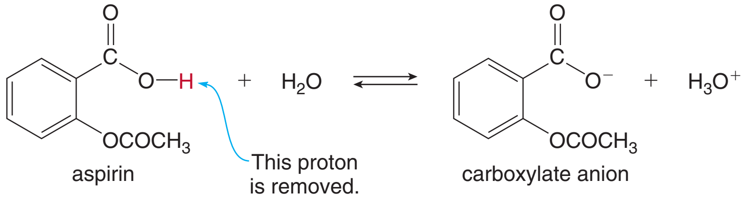
The word *aspirin* is derived from the prefix ***a-*** for *acetyl* + ***spir*** from the Latin name *spirea* for the meadowsweet plant.



Both salicylic acid and sodium salicylate, its sodium salt, were used to relieve pain in the nineteenth century, but both had undesirable side effects. Salicylic acid irritated the mucous membranes of the mouth and stomach, and sodium salicylate was too sweet for most patients. This prompted a search for a related compound that did not have these same drawbacks. In 1899, Felix Hoffman, a German chemist at Bayer Company, developed an economic commercial synthesis of acetylsalicylic acid, and aspirin was marketed to the general public. Hoffman's work was motivated by personal reasons; his father suffered from rheumatoid arthritis and he was unable to tolerate the sweet taste of sodium salicylate.

Aspirin was first used in medicine for its analgesic (pain-relieving), antipyretic (fever-reducing), and anti-inflammatory properties. Today it is also commonly used as an antiplatelet agent; that is, it is used to prevent blood clots from forming in arteries. In this way, it is used to treat and prevent heart attacks and strokes.

Like other carboxylic acids, **aspirin is a proton donor.** When aspirin is dissolved in water, an acid–base equilibrium occurs, and the carboxyl group (COOH) donates a proton to form its conjugate base, a carboxylate anion. Because it is a weak acid, only a small percentage of the carboxylic acid is ionized in water.



After ingestion, aspirin travels first into the stomach and then the intestines. In the acidic environment of the stomach, aspirin remains in its neutral form. When aspirin travels into the basic environment of the small intestines, however, aspirin is converted to its carboxylate anion, as shown in Figure 17.4. In the intestines, therefore, aspirin is predominantly in its ionic form.

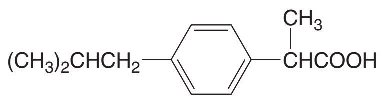
Why is this acid–base reaction important? **To be active, aspirin must cross a cell membrane, and to do so, it must be neutral, not ionic.** This means that aspirin crosses a cell membrane and is absorbed by the body in its neutral form in the stomach. Whether aspirin is present as its acid or its conjugate base is thus very important in determining whether it can enter a cell and act as a pain reliever and anti-inflammatory agent.

PROBLEM 17.22

Draw the acid–base reaction that occurs when aspirin is treated with NaOH.

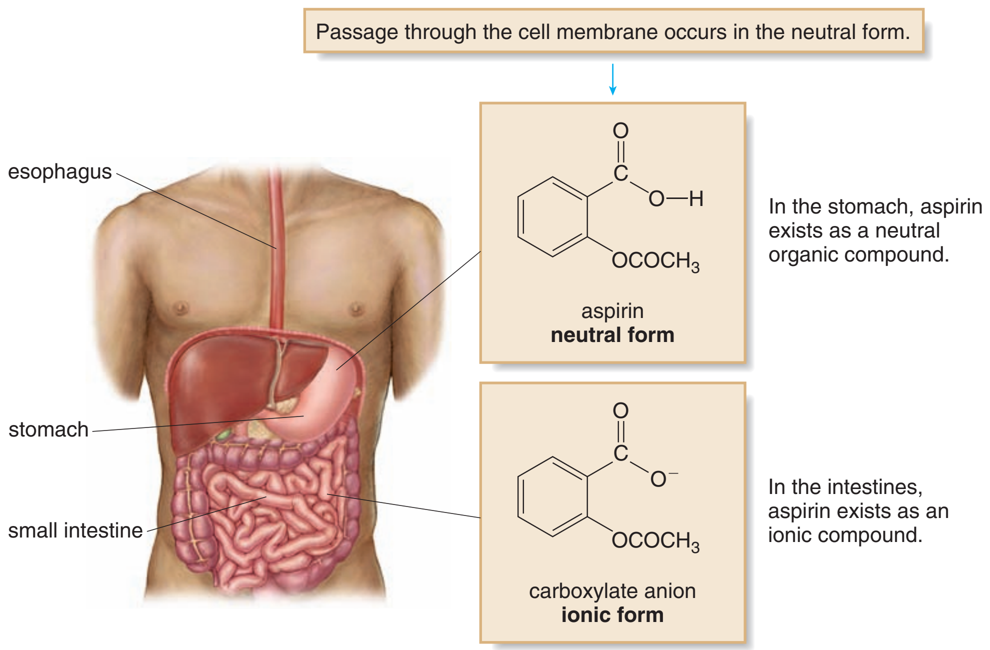
PROBLEM 17.23

Ibuprofen is another pain reliever that is a carboxylic acid. (a) Draw the acid–base reaction that occurs when ibuprofen is treated with NaOH. (b) What form of ibuprofen (neutral or ionic) exists in the stomach? (c) What form of ibuprofen exists in the intestines?



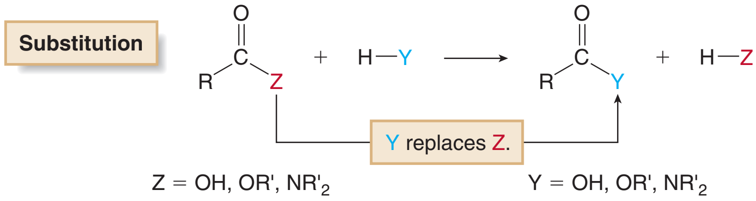
ibuprofen

FIGURE 17.4 The Acid–Base Chemistry of Aspirin

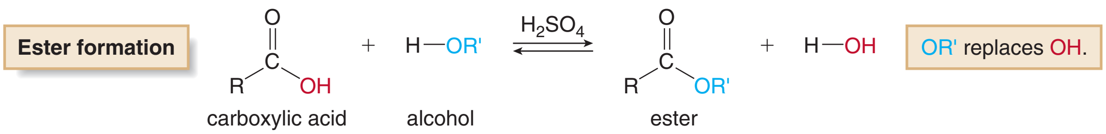


17.8 THE CONVERSION OF CARBOXYLIC ACIDS TO ESTERS AND AMIDES

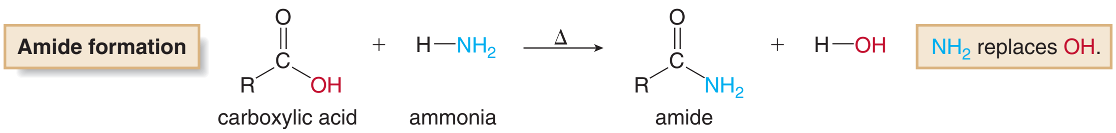
All acyl compounds undergo a common type of reaction—*substitution*. When an acyl compound (RCOZ) undergoes substitution, the group Z containing an electronegative atom bonded to the carbonyl carbon is *replaced* by another atom or group of atoms (Y).



For example, carboxylic acids react with alcohols to form esters and with ammonia to form amides.

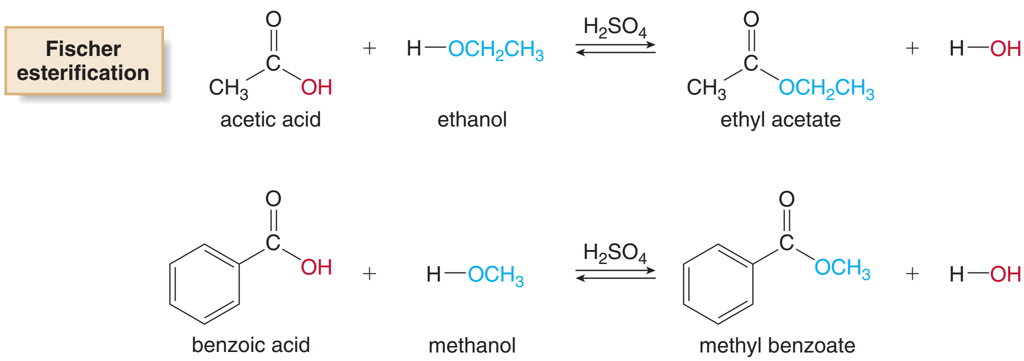


The Greek letter Δ (delta) is used over the arrow to indicate that a reaction requires heat (Section 5.1).



17.8A ESTER FORMATION

Treatment of a carboxylic acid (RCOOH) with an alcohol (R'OH) in the presence of an acid catalyst forms an ester (RCOOR'). This reaction is called a **Fischer esterification.** Esterification is a substitution because the OR' group of an alcohol replaces the OH group of the starting carboxylic acid.



CONSUMER NOTE

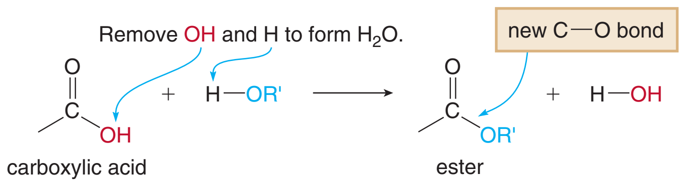
Ethyl acetate is a common organic solvent with a very characteristic odor. It is used in nail polish remover and model airplane glue.

This reaction is an equilibrium process. According to Le Châtelier's principle (Section 6.6), it is driven to the right by using excess alcohol or by removing the water as it is formed. Note where the elements of H_2O originate: the OH group comes from the carboxylic acid, and one H atom comes from the hydrogen of the alcohol (R'OH).

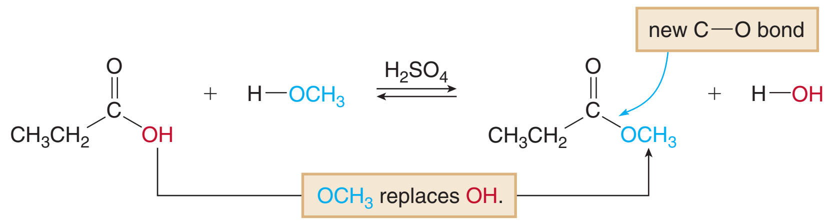
SAMPLE PROBLEM 17.5

What ester is formed when propanoic acid (CH_3CH_2COOH) is treated with methanol (CH_3OH) in the presence of H_2SO_4?

ANALYSIS To draw the products of any acyl substitution, arrange the carboxyl group of the carboxylic acid next to the functional group with which it reacts—the OH group of the alcohol in this case. Then, replace the OH group of the carboxylic acid by the OR' group of the alcohol, forming a new C—O bond at the carbonyl carbon.

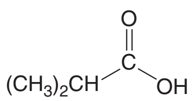


SOLUTION Replace the OH group of propanoic acid by the OCH_3 group of methanol to form the ester.

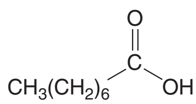


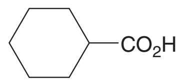
PROBLEM 17.24

What ester is formed when each carboxylic acid is treated with ethanol (CH_3CH_2OH) in the presence of H_2SO_4?

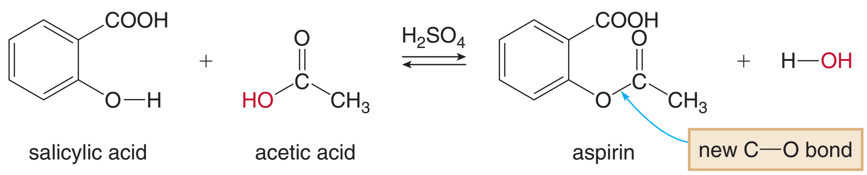
a. 

b. HCO_2H

c. 

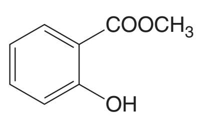
d. 

Fischer esterification can be used to synthesize aspirin from salicylic acid.



PROBLEM 17.25

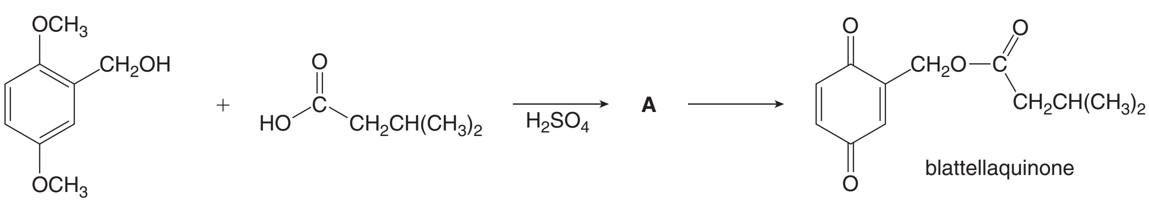
Methyl salicylate is the major component of the oil of wintergreen (Section 17.5). What carboxylic acid and alcohol are needed to synthesize methyl salicylate by Fischer esterification?



methyl salicylate

PROBLEM 17.26

Identify **A** in the following reaction. **A** was converted in one step to blattellaquinone, the sex pheromone of the female German cockroach, *Blattella germanica*.



ENVIRONMENTAL NOTE



A short laboratory synthesis of the ester blattellaquinone, the sex pheromone of the female German cockroach (Problem 17.26), opens new possibilities for cockroach population control using pheromone-baited traps.

HEALTH NOTE

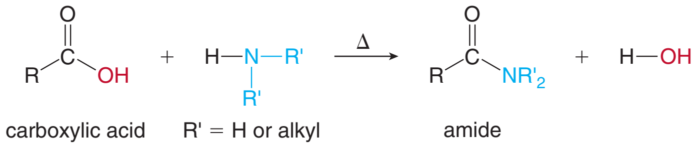


Insect repellents containing DEET have become particularly popular because of the spread of many insect-borne diseases, such as West Nile virus and Lyme disease. DEET does not kill insects—it repels them. It is thought that DEET somehow confuses insects so that they can no longer sense the warm moist air that surrounds a human body.

17.8B AMIDE FORMATION

Heating a carboxylic acid (RCOOH) with ammonia (NH_3) or an amine ($R'NH_2$ or R'_2NH) forms an amide. Formation of an amide from a carboxylic acid is a substitution because the OH group of the acid is replaced by a nitrogen-containing group.

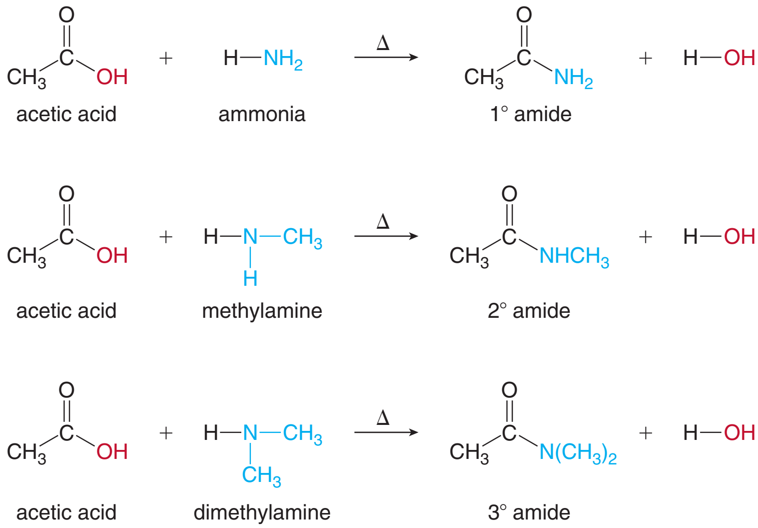
Amide formation



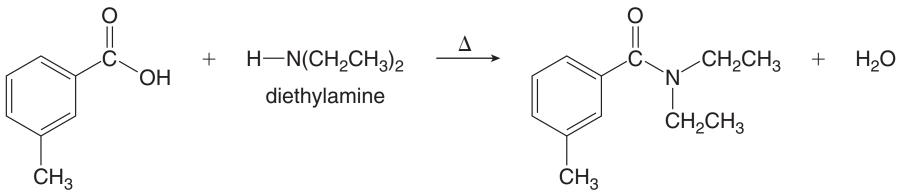
The identity of the nitrogen compound determines the type of amide formed.

- Reaction of RCOOH with NH_3 forms a 1° amide ($RCONH_2$).
- Reaction of RCOOH with $R'NH_2$ forms a 2° amide (RCONHR').
- Reaction of RCOOH with R'_2NH forms a 3° amide ($RCONR'_2$).

Examples



Useful amides can be made by this reaction. Heating carboxylic acid **X** with diethylamine forms the 3° amide *N,N*-diethyl-*m*-toluamide, popularly known as **DEET.** DEET, the active ingredient in the most widely used insect repellents, is effective against mosquitoes, fleas, and ticks.



X

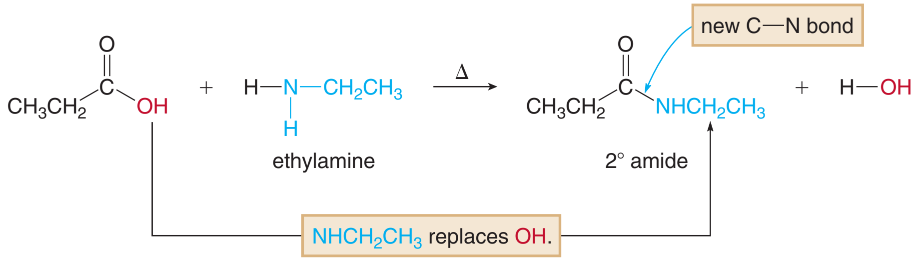
N,N-diethyl-*m*-toluamide (DEET)

SAMPLE PROBLEM 17.6

What amide is formed when propanoic acid (CH_3CH_2COOH) is heated with ethylamine ($CH_3CH_2NH_2$)?

ANALYSIS To draw the products of amide formation, arrange the carboxyl group of the carboxylic acid next to the H—N bond of the amine. Then, replace the OH group of the carboxylic acid by the $NHCH_2CH_3$ group of the amine, forming a new C—N bond at the carbonyl carbon.

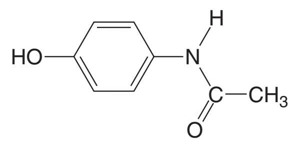
SOLUTION Reaction of RCOOH with an amine that has one alkyl group on the N atom ($R'NH_2$) forms a 2° amide (RCONHR').



PROBLEM 17.27 What amide is formed when $CH_3CH_2CH_2CH_2COOH$ is treated with each compound?

a. NH_3 b. $(CH_3)_2NH$ c. cyclohexyl–NH_2 d. CH_3NH_2

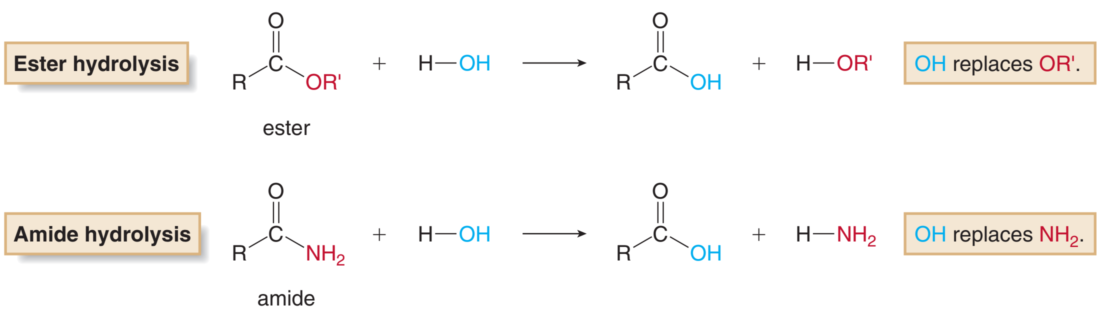
PROBLEM 17.28 What carboxylic acid and amine are needed to synthesize acetaminophen, the active pain reliever in Tylenol?



acetaminophen

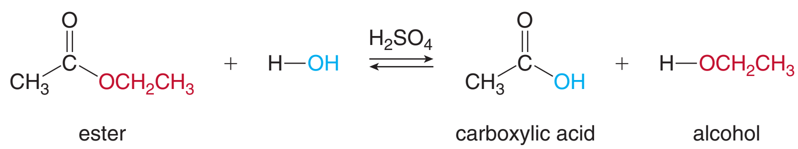
17.9 HYDROLYSIS OF ESTERS AND AMIDES

Esters and amides undergo substitution at the carbonyl carbon as well. For example, **esters and amides react with water to form carboxylic acids.** This reaction is another example of **hydrolysis,** since bonds are cleaved on reaction with water.

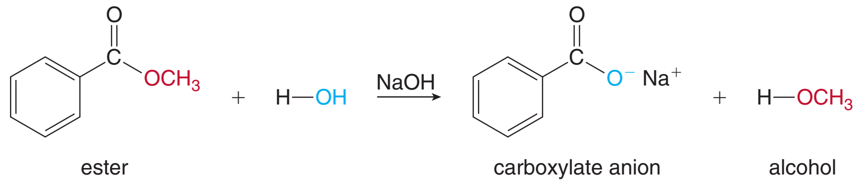


17.9A ESTER HYDROLYSIS

Esters are hydrolyzed with water in the presence of acid or base. **Treatment of an ester (RCOOR') with water in the presence of an acid catalyst forms a carboxylic acid (RCOOH) and a molecule of alcohol (R'OH).** The hydrolysis of esters in aqueous acid is an equilibrium reaction that is driven to the right by using a large excess of water.



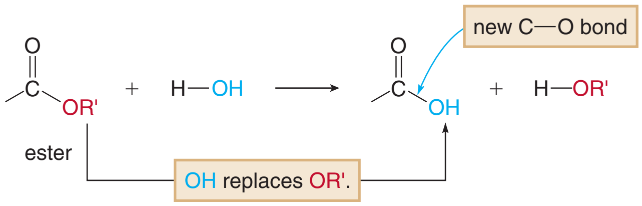
Esters are hydrolyzed in aqueous base to form carboxylate anions and a molecule of alcohol. Basic hydrolysis of an ester is called **saponification.**



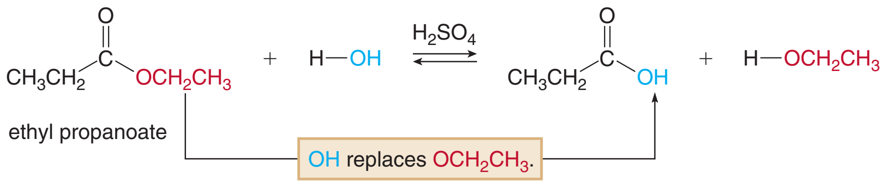
SAMPLE PROBLEM 17.7

What products are formed when ethyl propanoate ($CH_3CH_2CO_2CH_2CH_3$) is hydrolyzed with water in the presence of H_2SO_4?

ANALYSIS To draw the products of hydrolysis in acid, replace the OR' group of the ester by an OH group from water, forming a new C—O bond at the carbonyl carbon. A molecule of alcohol (R'OH) is also formed from the alkoxy group (OR') of the ester.

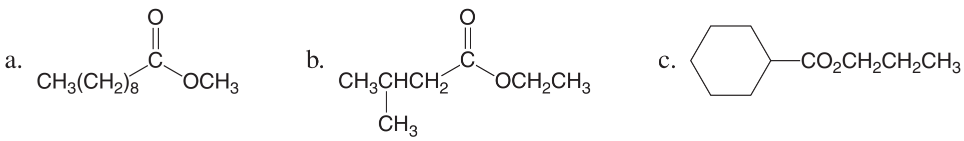


SOLUTION Replace the OCH_2CH_3 group of ethyl propanoate by the OH group of water to form propanoic acid ($CH_3CH_2CO_2H$) and ethanol (CH_3CH_2OH).



PROBLEM 17.29

What products are formed when each ester is treated with H_2O and H_2SO_4?

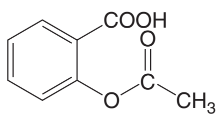


PROBLEM 17.30

What products are formed when each ester in Problem 17.29 is treated with H_2O and NaOH?

PROBLEM 17.31

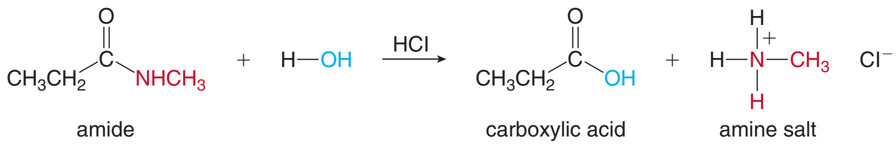
Aspirin cannot be sold as a liquid solution for children because it slowly undergoes hydrolysis in water. What products are formed when aspirin is hydrolyzed?



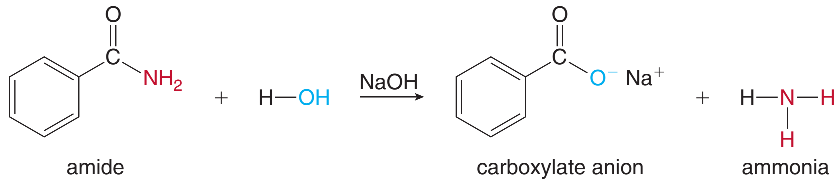
aspirin

17.9B AMIDE HYDROLYSIS

Amides are much less reactive than esters in substitution reactions. Nonetheless, under forcing conditions amides can be hydrolyzed with water in the presence of acid or base. **Treatment of an amide (RCONHR') with water in the presence of an acid catalyst (HCl) forms a carboxylic acid (RCOOH) and an amine salt ($R'NH_3^+$ Cl^-).**



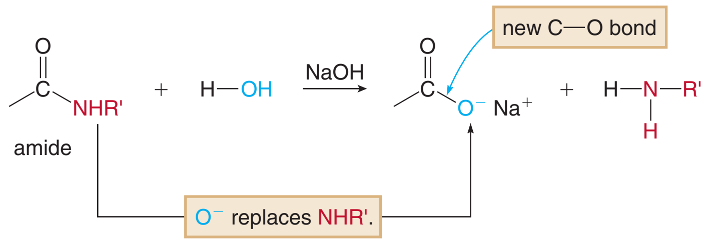
Amides are also hydrolyzed in aqueous base to form carboxylate anions and a molecule of ammonia (NH_3) or amine.



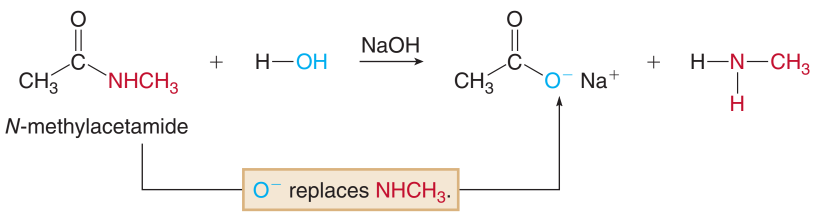
The relative lack of reactivity of the amide bond is important in the proteins in the body. Proteins are polymers connected by amide linkages, as we will learn in Chapter 21. Proteins are stable in water in the absence of acid or base, so they can perform their various functions in the cell without breaking down. The hydrolysis of the amide bonds in proteins requires a variety of specific enzymes.

SAMPLE PROBLEM 17.8 What products are formed when *N*-methylacetamide ($CH_3CONHCH_3$) is hydrolyzed with water in the presence of NaOH?

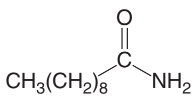
ANALYSIS To draw the products of amide hydrolysis in base, replace the NHR' group of the amide by an oxygen anion (O^-), forming a new C—O bond at the carbonyl carbon. A molecule of amine ($R'NH_2$) is also formed from the nitrogen group (NHR') of the amide.

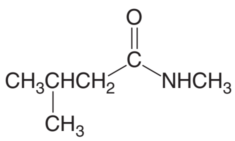


SOLUTION Replace the $NHCH_3$ group of *N*-methylacetamide by a negatively charged oxygen atom (O^-) to form sodium acetate ($CH_3CO_2^-$ Na^+) and methylamine (CH_3NH_2).



PROBLEM 17.32 What products are formed when each amide is treated with H_2O and H_2SO_4?

a. 

b. 

c. 

PROBLEM 17.33 What products are formed when each amide in Problem 17.32 is treated with H_2O and NaOH?

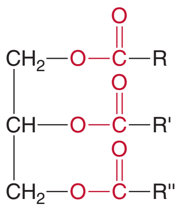
CONSUMER NOTE



This product contains the "fake fat" olestra, giving it fewer calories for the calorie-conscious consumer.

17.9C FOCUS ON HEALTH & MEDICINE OLESTRA, A SYNTHETIC FAT

The most prevalent naturally occurring esters are the **triacylglycerols.** ***Triacylglycerols*** **contain three ester groups, each having a long carbon chain (abbreviated as R, R', and R'') bonded to the carbonyl group.** Triacylglycerols are **lipids;** that is, they are water-insoluble organic compounds found in biological systems. Animal fats and vegetable oils are composed of triacylglycerols.

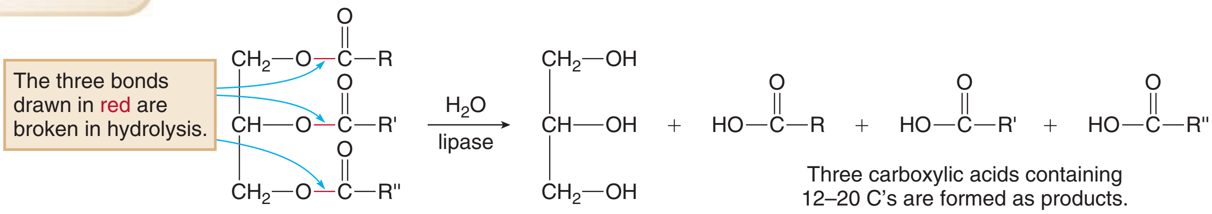


R groups have 11–19 C's.

[Three ester groups are labeled in red.]

triacylglycerol

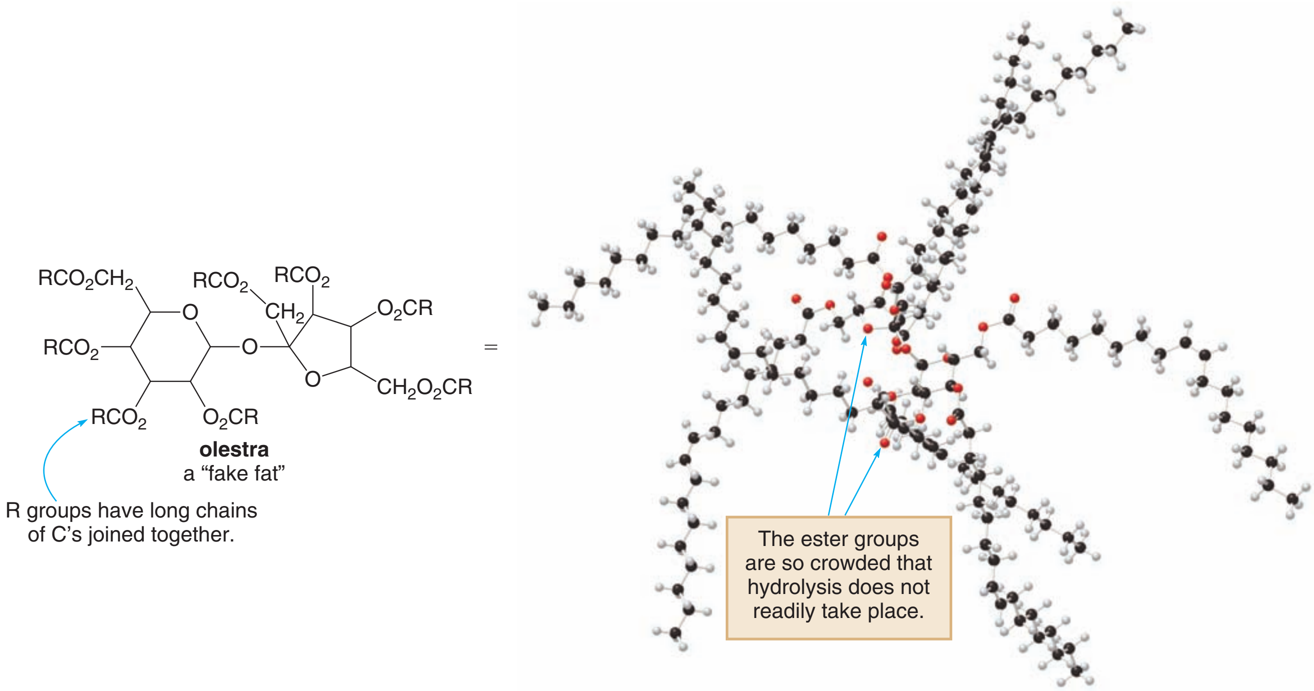
Animals store energy in the form of triacylglycerols kept in a layer of fat cells below the surface of the skin. This fat serves to insulate the organism, as well as provide energy for its metabolic needs for long periods of time. The first step in the metabolism of a triacylglycerol is hydrolysis of the ester bonds to form glycerol and three fatty acids—long-chain carboxylic acids. **This reaction is simply ester hydrolysis.** In cells, this reaction is carried out with enzymes called **lipases.**



triacylglycerol glycerol

The fatty acids produced on hydrolysis are then oxidized, yielding CO_2 and H_2O, as well as a great deal of energy. Diets high in fat content can lead to a large amount of stored fat, ultimately causing an individual to be overweight. One recent attempt to reduce calories in common snack foods has been to substitute "fake fats" such as **olestra** (trade name: **Olean**) for triacylglycerols.

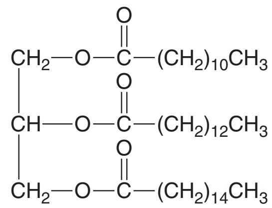
We will learn more about triacylglycerols in Chapter 19.



Olestra has many ester groups formed from long-chain carboxylic acids and sucrose, the sweet-tasting carbohydrate in table sugar. Olestra has many properties similar to the triacylglycerols in fats and oils. In one way, however, olestra is different. Olestra has so many ester units clustered together that they are too crowded to be hydrolyzed. As a result, olestra is *not* metabolized nor is it absorbed. Instead, it passes through the body unchanged, *providing no calories to the consumer.*

PROBLEM 17.34

What products are formed when the following triacylglycerol is hydrolyzed with water and H_2SO_4?



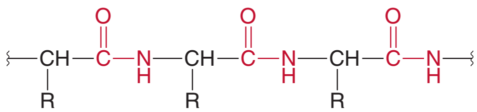
CONSUMER NOTE



DuPont built the first commercial nylon plant in 1938. Although it was initially used by the military to make parachutes, nylon quickly replaced silk in many common clothing articles after World War II.

17.10 SYNTHETIC POLYMERS IN MODERN SOCIETY—POLYAMIDES AND POLYESTERS

All natural and synthetic fibers are polymers. Natural fibers are obtained from either plant or animal sources, and this determines the fundamental nature of their chemical structure. Fibers like **wool and silk obtained from animals are proteins,** and so they are joined together by many amide linkages.



wool and silk—polymers with many amide bonds (labeled in red)

An important practical application of organic chemistry has been the synthesis of synthetic fibers, many of which have properties that are different from and sometimes superior to their naturally occurring counterparts. Two common classes of synthetic polymers are polyamides and polyesters.

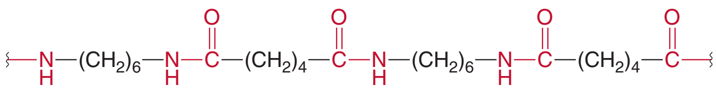
CONSUMER NOTE



Nylon is used in a wide variety of consumer products, including rope, fabric, backpacks, hot air balloons, and parachutes. Nylon sutures are used in medicine.

17.10A NYLON—A POLYAMIDE

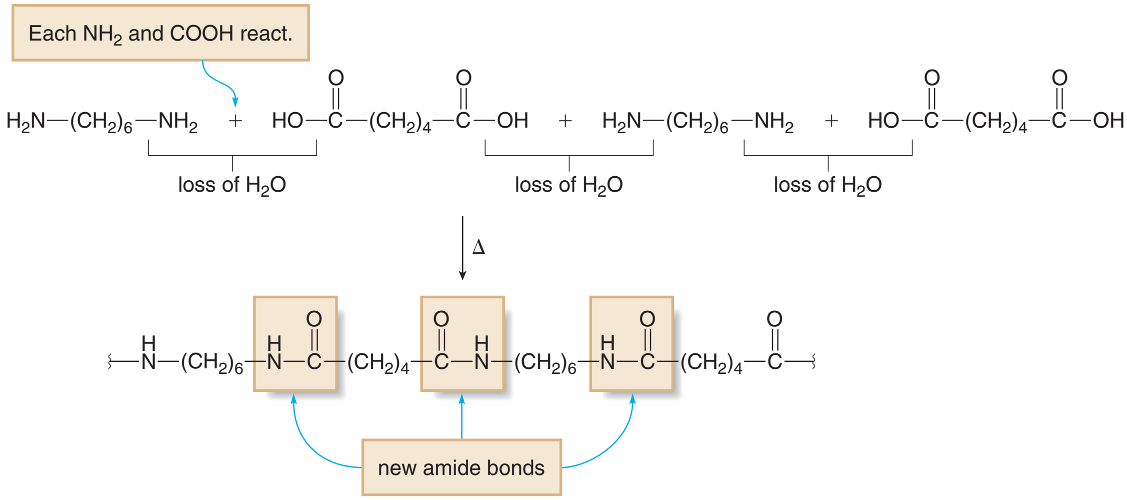
The search for a synthetic fiber with properties similar to silk led to the discovery of **nylon,** a **polyamide.** There are several different kinds of nylon, but the best known is nylon 6,6.



nylon 6,6
[The amide bonds are labeled in red.]

To synthesize nylon 6,6, two monomers are needed. Each monomer has six carbons (hence its name) and two functional groups. One monomer is a dicarboxylic acid, adipic acid [$\mathbf{HO_2C(CH_2)_4CO_2H}$], and the second monomer is a diamine, hexamethylenediamine [$\mathbf{H_2N(CH_2)_6NH_2}$]. Heating the two monomers together at high temperature forms the amide bonds of the long polymer chain. When each amide is formed, a molecule of H_2O is lost from the starting materials. Nylon is an example of a **condensation polymer.**

Polymers were first discussed in detail in Section 13.8.



nylon 6,6

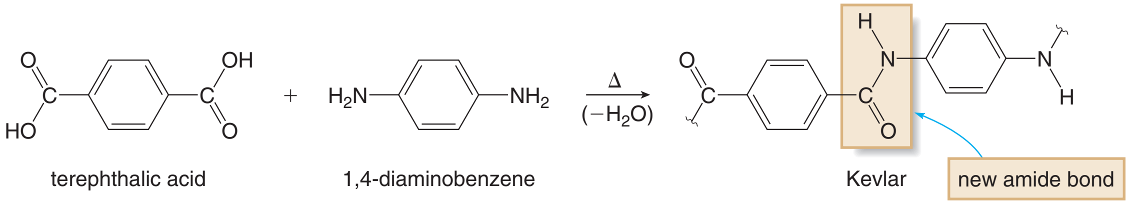
CONSUMER NOTE



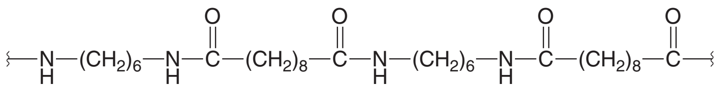
Armadillo bicycle tires reinforced with Kevlar are hard to pierce with sharp objects, so a cyclist rarely gets a flat tire.

- A *condensation polymer* is a polymer formed when monomers containing two functional groups come together with loss of a small molecule such as water.

Kevlar is a polyamide formed from terephthalic acid and 1,4-diaminobenzene. The aromatic rings of the polymer backbone make the chains less flexible than those of nylon 6,6, resulting in a very strong material. Kevlar is light in weight compared to other materials that are similar in strength, so it is used in many products, such as bulletproof vests, army helmets, and the protective clothing used by fire fighters.



PROBLEM 17.35 What two monomers are needed to prepare nylon 6,10?

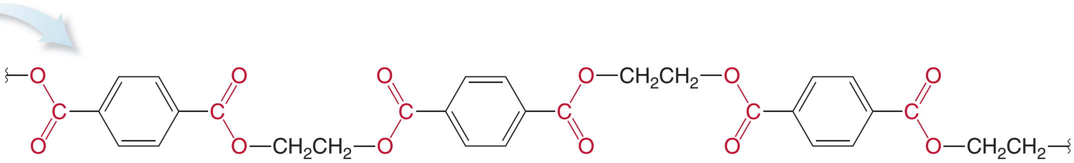


nylon 6,10

17.10B POLYESTERS

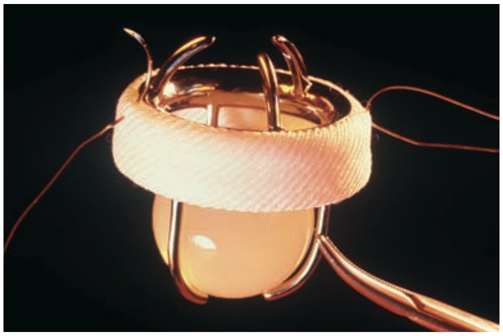
Polyesters constitute a second major class of condensation polymers. The most common polyester is polyethylene terephthalate (**PET**), which is sold under a variety of trade names depending on its use (Dacron, Terylene, and Mylar). Plastic soft drink bottles are made of PET.



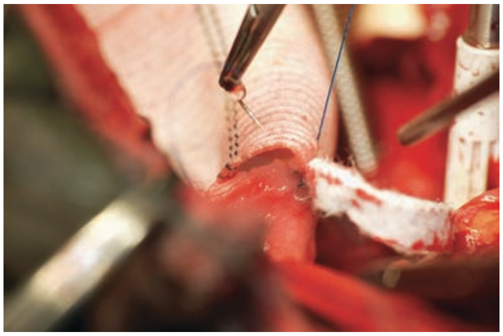


polyethylene terephthalate
PET
[Ester bonds are drawn in red.]

FIGURE 17.5 Medical Uses of PET

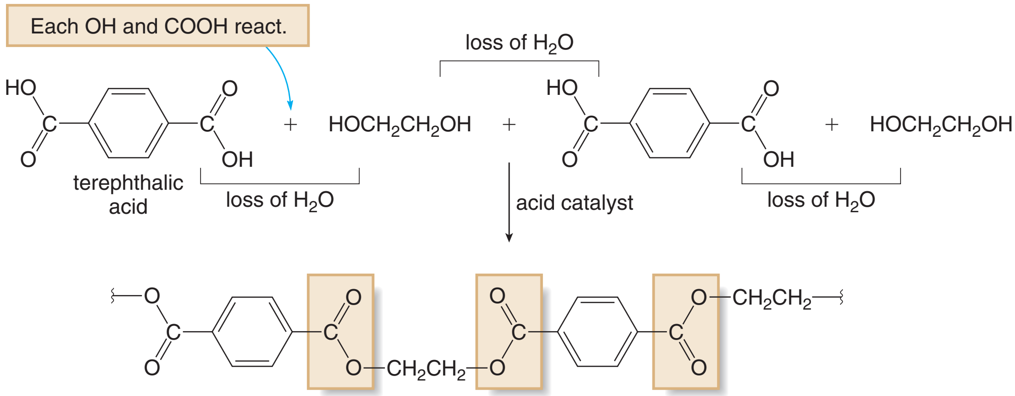


a. PET is used to make the knitted material present in artificial heart valves.



b. Some replacement blood vessels are made with PET.

One method of synthesizing PET is by the acid-catalyzed reaction of a dicarboxylic acid (terephthalic acid) with ethylene glycol ($HOCH_2CH_2OH$) in a Fischer esterification reaction.

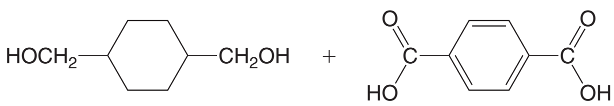


polyethylene terephthalate
PET

Because these polymers are easily and cheaply prepared and they form strong and chemically stable materials, they have been used in clothing, films, tires, and plastic drink bottles. Polyester fiber is also used in artificial heart valves and replacement blood vessels (Figure 17.5).

PROBLEM 17.36

Draw the structure of Kodel, a polyester formed from 1,4-dihydroxymethylcyclohexane and terephthalic acid. Suggest a reason why fabrics made from Kodel are stiff and crease resistant.

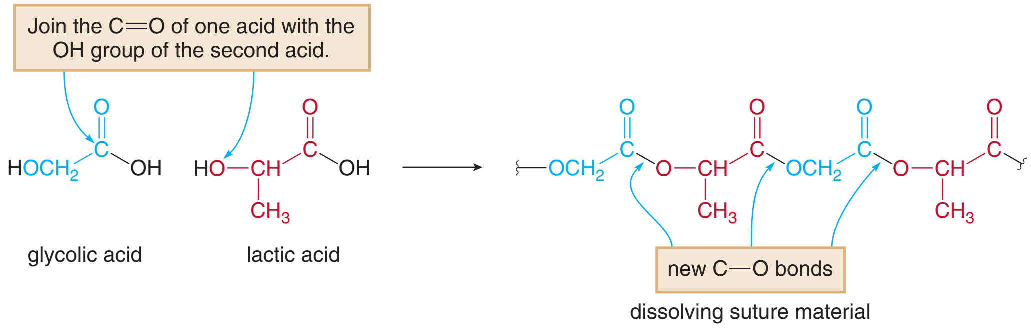


1,4-dihydroxymethylcyclohexane terephthalic acid

17.10C FOCUS ON HEALTH & MEDICINE DISSOLVING SUTURES

Although PET is a stable material, the ester bonds in some other polyesters are quite readily hydrolyzed to carboxylic acids and alcohols in aqueous medium. Polyesters of this sort are suited for applications in which slow degradation is a useful feature. One example of a degradable

polymer is formed from two α-hydroxy acids—glycolic acid ($HOCH_2COOH$) and lactic acid [$CH_3CH(OH)COOH$].



When glycolic acid and lactic acid are combined, the hydroxyl group of one α-hydroxy acid reacts with the carboxyl group of the second α-hydroxy acid. The resulting polymer is used by surgeons in dissolving sutures. Within weeks, the polymer is hydrolyzed to the monomers from which it was prepared, which are metabolized readily by the body. These sutures are used internally to hold tissues together while healing and scar formation occur.

17.10D FOCUS ON THE ENVIRONMENT POLYMER RECYCLING

CONSUMER NOTE

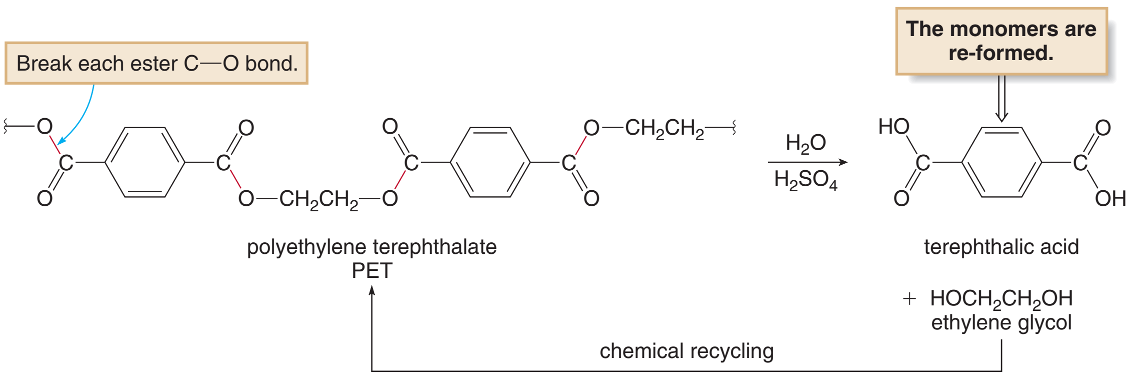


The lower the recycling code, the easier the polymer is to recycle.

The same desirable characteristics that make polymers popular materials for consumer products—durability, strength, and lack of reactivity—also contribute to environmental problems. Many polymers do not degrade readily, and as a result, billions of pounds of polymers end up in landfills every year. Recycling polymers is one way to help combat the waste problem they create.

The most common polymers are each assigned a recycling code (1–6); **the lower the number, the easier the polymer is to recycle.** PET materials are assigned recycling code "1" because they are the easiest to recycle. Since recycled polymers are often still contaminated with small amounts of adhesives and other materials, these recycled polymers are generally not used for storing food or drink products. Recycled PET is used to make fibers for fleece clothing and carpeting.

PET can also be converted back to the monomers from which it was made. For example, heating PET with water and acid breaks the ester bonds of the polymer chain to give ethylene glycol ($HOCH_2CH_2OH$) and terephthalic acid. These monomers then serve as starting materials for more PET.



PROBLEM 17.37 A polyester can be converted back to the monomers from which it is made much more easily than a polymer like polyethylene, [—CH_2CH_2—]$_n$. Explain why this is so.



Penicillin was used to treat injured soldiers in World War II before its structure had been conclusively determined.

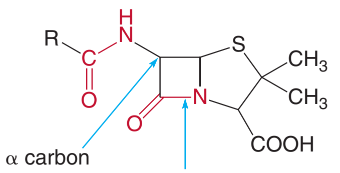
17.11 FOCUS ON HEALTH & MEDICINE PENICILLIN

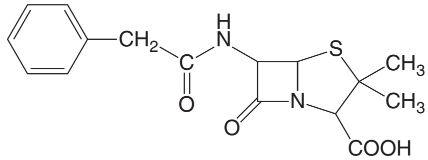
In the twenty-first century it is hard to imagine that an infected cut or scrape could be life-threatening. Before antibiotics were discovered in the early twentieth century, however, that was indeed the case.

The antibiotic properties of **penicillin** were first discovered in 1928 by Sir Alexander Fleming, who noticed that a mold of the genus *Penicillium* inhibited the growth of certain bacteria. After years of experimentation, penicillin was first used to treat a female patient who had developed a streptococcal infection in 1942. By 1944, penicillin production was given high priority by the United States government, because it was needed to treat the many injured soldiers in World War II.

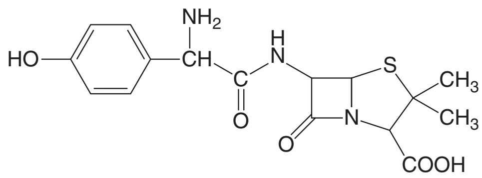
The penicillins are a group of related antibiotics. All penicillins contain two amide units. One amide is part of a four-membered ring called a **β-lactam.** The second amide is bonded to the α carbon of the β-lactam carbonyl group. Particular penicillins differ in the identity of the R group in the amide side chain. The first penicillin to be discovered was penicillin G. Amoxicillin is another example in common use today.

General structure Penicillin





penicillin G



amoxicillin

Unlike mammalian cells, bacterial cells are surrounded by a fairly rigid cell wall, which allows the bacterium to live in many different environments. **Penicillin interferes with the synthesis of the bacterial cell wall.** Penicillin kills bacteria by a substitution reaction that occurs at the amide that is part of the β-lactam. The β-lactam is more reactive than a regular amide because the bond angles in the small ring must be 90°. This feature makes the ring unstable. The β-lactam ring of the penicillin molecule reacts with an enzyme needed to synthesize the cell wall, and this deactivates the enzyme. Cell wall construction is halted, killing the bacterium. This process is discussed further in Section 21.9C.

Penicillin has no effect on mammalian cells because they are surrounded by a flexible membrane composed of a lipid bilayer (Chapter 19) and not a cell wall.

PROBLEM 17.38 How many chirality centers does penicillin G contain?

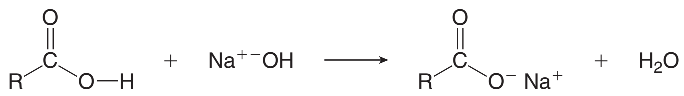
CHAPTER HIGHLIGHTS

KEY TERMS

Acyl group (17.1)
Alpha (α) carbon (17.2)
Amide (17.1)
Beta (β) carbon (17.2)
Carboxyl group (17.1)
Carboxylate anion (17.6)
Carboxylic acid (17.1)
Condensation polymer (17.10)
Ester (17.1)
Fischer esterification (17.8)
Hydrolysis (17.9)
α-Hydroxy acid (17.4)
Lactam (17.1)
Lactone (17.1)
Lipid (17.9)
Micelle (17.6)
Nylon (17.10)
Penicillin (17.11)
Polyamide (17.10)
Polyester (17.10)
Primary (1°) amide (17.1)
Prostaglandin (17.4)
Saponification (17.9)
Secondary (2°) amide (17.1)
Soap (17.6)
Tertiary (3°) amide (17.1)
Triacylglycerol (17.9)

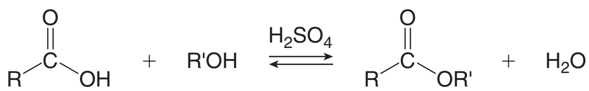
KEY REACTIONS

[1] Acid–base reaction of carboxylic acids (17.6)

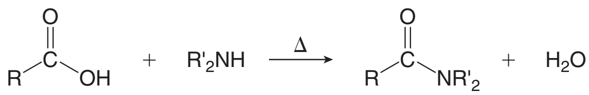


[2] Substitution reactions of carboxylic acids (17.8)

a. Formation of esters



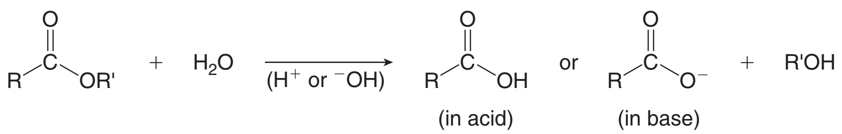
b. Formation of amides



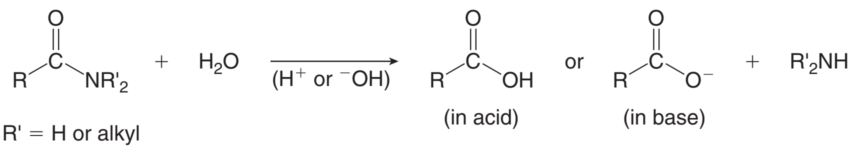
R' = H or alkyl

[3] Hydrolysis of acyl compounds (17.9)

a. Ester hydrolysis



b. Amide hydrolysis



R' = H or alkyl

KEY CONCEPTS

1 What are the characteristics of carboxylic acids, esters, and amides?

- Carboxylic acids have the general structure RCOOH; esters have the general structure RCOOR'; amides have the general structure $RCONR'_2$, where R' = H or alkyl. (17.1)
- The carbonyl carbon is trigonal planar with bond angles of 120°. (17.1)
- All acyl compounds have a polar C═O. RCO_2H, $RCONH_2$, and RCONHR' are capable of intermolecular hydrogen bonding. (17.3)

2 How are carboxylic acids, esters, and amides named? (17.2)

- Carboxylic acids are identified by the suffix *-oic acid.*
- Esters are identified by the suffix *-ate.*
- Amides are identified by the suffix *-amide.*

3 Give examples of useful carboxylic acids. (17.4)

- α-Hydroxy carboxylic acids are used in skin care products.
- Aspirin, ibuprofen, and naproxen are pain relievers and anti-inflammatory agents.
- Aspirin is an anti-inflammatory agent because it blocks the synthesis of prostaglandins from arachidonic acid.

4 Give examples of useful esters and amides. (17.5)

- Some esters—ethyl butanoate, pentyl butanoate, and methyl salicylate—have characteristic odors and flavors.
- Benzocaine is the active ingredient in over-the-counter oral topical anesthetics.
- Acetaminophen is the active ingredient in Tylenol.

5 What products are formed when carboxylic acids are treated with base? (17.6)

- Carboxylic acids react with bases to form carboxylate anions ($RCOO^-$).
- Carboxylate anions are water soluble and commonly used as preservatives.

6 How does soap clean away dirt? (17.6C)

- Soaps are salts of carboxylic acids that have many carbon atoms in a long hydrocarbon chain. A soap molecule has an ionic head and a nonpolar hydrocarbon tail.
- Soap forms micelles in water with the polar heads on the surface and the hydrocarbon tails in the interior. Grease and dirt dissolve in the nonpolar tails, so they can be washed away with water.

7 Discuss the acid–base chemistry of aspirin. (17.7)

- Aspirin remains in its neutral form in the stomach, and in this form it can cross a cell membrane and serve as an anti-inflammatory agent.
- A proton is removed from aspirin in the basic environment of the intestines to form an ionic carboxylate anion. This form is not absorbed.

8 How are carboxylic acids converted to esters and amides? (17.8)

- Carboxylic acids are converted to esters by reaction with alcohols (R'OH) and acid (H_2SO_4).
- Carboxylic acids are converted to amides by heating with ammonia (NH_3) or amines ($R'NH_2$ or R'_2NH).

9 What hydrolysis products are formed from esters and amides? (17.9)

- Esters are hydrolyzed to carboxylic acids (RCOOH) in the presence of an acid catalyst (H_2SO_4). Esters are converted to carboxylate anions ($RCOO^-$) with aqueous base (NaOH in H_2O).
- Amides are hydrolyzed to carboxylic acids (RCOOH) in the presence of an acid catalyst (HCl). Amides are converted to carboxylate anions ($RCOO^-$) with aqueous base (NaOH in H_2O).

10 What are polyamides and polyesters and how are they formed? (17.10)

- Polyamides like nylon are polymers that contain many amide bonds. They are formed when a dicarboxylic acid is heated with a diamine.
- Polyesters like PET are polymers that contain many ester bonds. They are formed when a dicarboxylic acid is treated with a diol in the presence of acid (H_2SO_4).

11 How does penicillin act as an antibiotic? (17.11)

- The β-lactam of penicillin is more reactive than a regular amide and it reacts with an enzyme needed to synthesize the cell wall of a bacterium. Without a cell wall, the bacterium dies.

PROBLEMS

Selected in-chapter and end-of-chapter problems have brief answers provided in Appendix B.

Structure and Bonding

17.39 Draw the structure of a compound that fits each description:

a. a carboxylic acid of molecular formula $C_8H_{16}O_2$ that has six carbons in its longest chain
b. an ester of molecular formula $C_6H_{12}O_2$ that contains a methoxy group (OCH_3) bonded to the carbonyl group
c. an ester of molecular formula $C_6H_{10}O_2$ that contains a ring
d. a carboxylic acid of molecular formula $C_6H_{10}O_2$ that has the carboxyl group bonded to a ring

17.40 Draw the structure of a constitutional isomer of octanoic acid [$CH_3(CH_2)_6CO_2H$] that:

a. contains a carboxyl group and no chirality center
b. contains a carboxyl group and a chirality center
c. contains an ester

17.41 Draw the structure of a compound of molecular formula $C_5H_{11}NO$ that contains: (a) a 1° amide; (b) a 2° amide; (c) a 3° amide.

17.42 Draw the structure of a compound of molecular formula $C_9H_{11}NO$ that contains a benzene ring and: (a) a 1° amide; (b) a 2° amide; (c) a 3° amide.

17.43 Draw the structure of four constitutional isomers of molecular formula $C_4H_8O_2$ that contain an ester.

17.44 Draw the structure of four constitutional isomers of molecular formula $C_5H_{10}O_2$ that have the general formula HCO_2R; that is, compounds that are esters of formic acid, HCO_2H.

17.45 Can a lactam be a 1° amide?

17.46 Can a lactam be a 3° amide?

17.47 What is the difference between a lactone and a lactam?

17.48 What is the difference between a lactone and an ester?

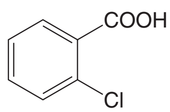
Nomenclature

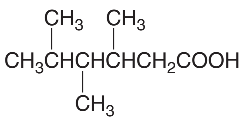
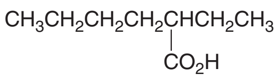
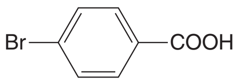
17.49 Give an acceptable name for each carboxylic acid.

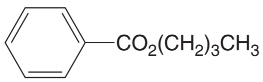
a. $(CH_3)_2CHCH_2CH_2COOH$

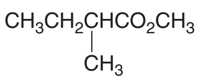
b. $CH_3CH_2CH_2CH(CH_2CH_3)CH(CH_2CH_3)CH_2CH_2COOH$

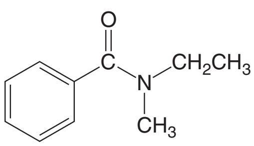
c. $CH_3CH_2CH_2CH_2CH_2CH(CO_2H)CH_2CH_3$

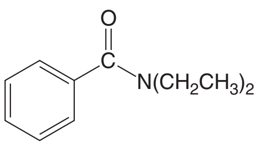
d. 

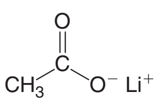
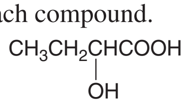
17.50 Give an acceptable name for each carboxylic acid.
a. $(CH_3)_2CHCH_2CH_2CH_2CH_2CH_2COOH$
b. 
c. 
d. 

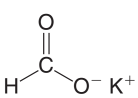
17.51 Give an acceptable name for each ester.
a. $CH_3CH_2CH_2CO_2CH_2CH_2CH_3$
b. $HCOOCH_2CH_3$
c. 

17.52 Give an acceptable name for each ester.
a. $CH_3CO_2(CH_2)_4CH_3$
b. $HCO_2(CH_2)_5CH_3$
c. 

17.53 Give an acceptable name for each amide.
a. $CH_3(CH_2)_4CONH_2$
b. $HCONHCH_2CH_2CH_2CH_3$
c. 

17.54 Give an acceptable name for each amide.
a. $CH_3(CH_2)_6CONH_2$
b. 
c. $(CH_3)_2CHCH_2CH_2CONH_2$

17.55 Give an acceptable name for each compound.
a. $HCONH_2$
b. 
c. 
d. $CH_3CH_2CO_2CH_2CH_2CH_3$

17.56 Give an acceptable name for each compound.
a. $CH_3(CH_2)_8CO_2CH_3$
b. $(CH_3)_2CHCH_2CONH_2$
c. 
d. $(CH_3)_3C(CH_2)_3COOH$

17.57 Draw the structure corresponding to each name.
a. 2-hydroxyheptanoic acid
b. 4-chlorononanoic acid
c. 3,4-dibromobenzoic acid
d. lithium propanoate
e. 2,2-dibromobutanoic acid
f. ethyl 2-methylpropanoate
g. potassium butanoate

17.58 Draw the structure corresponding to each name.
a. 3-methylhexanoic acid
b. 3-hydroxy-4-methylheptanoic acid
c. *p*-nitrobenzoic acid
d. sodium hexanoate
e. *m*-ethylbenzoic acid
f. propyl decanoate
g. lithium heptanoate

17.59 Draw the structure corresponding to each name.
a. propyl formate
b. butyl butanoate
c. heptyl benzoate
d. *N*-ethylhexanamide
e. *N*-ethyl-*N*-methylheptanamide

17.60 Draw the structure corresponding to each name.
a. octyl acetate
b. hexyl pentanoate
c. propyl hexanoate
d. *N*-butylbenzamide
e. *N,N*-dimethyloctanamide

17.61 What is the difference between *N*-methylbutanamide and 2-methylbutanamide? Draw structures to illustrate the difference.

17.62 What is the difference between *N*-ethylpentanamide and 3-ethylpentanamide? Draw structures to illustrate the difference.

17.63 Draw the structures for the four carboxylic acids of molecular formula $C_5H_{10}O_2$. Give the IUPAC name for each compound.

17.64 Draw the structures for the four sodium salts of the carboxylic acids in Problem 17.63, formed by treating each of these carboxylic acids with NaOH. Give the IUPAC name for each sodium salt.

Physical Properties and Intermolecular Forces

17.65 Which compound(s) can hydrogen bond to another molecule like itself? Which compounds can hydrogen bond to water? (a) HCO_2CH_3; (b) $CH_3CH_2CO_2H$.

17.66 Which compound(s) can hydrogen bond to another molecule like itself? Which compounds can hydrogen bond to water? (a) $CH_3CONHCH_3$; (b) $HCON(CH_3)_2$.

17.67 Rank the following compounds in order of increasing boiling point: $CH_3CH_2CH(CH_3)_2$, $CH_3CH_2CO_2H$, and $CH_3CH_2COCH_3$.

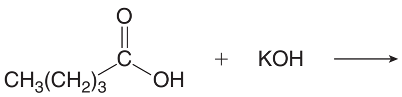
17.68 Rank the following compounds in order of increasing boiling point: $(CH_3)_2CHCO_2H$, $CH_3CH_2CO_2CH_3$, $(CH_3)_2CHCH(CH_3)_2$.

17.69 Explain why the boiling point of $CH_3CH_2CONH_2$ is higher than the boiling point of $CH_3CO_2CH_3$.

17.70 Which compound in each pair is more water soluble? Which compound in each pair is more soluble in an organic solvent? (a) $CH_3CH_2CH_2CH_3$ or $CH_3CH_2CH_2CH_2CO_2H$; (b) $CH_3(CH_2)_4COOH$ or $CH_3(CH_2)_4COO^- Na^+$.

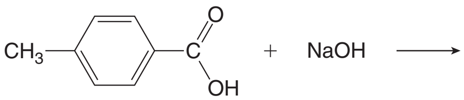
Acidity

17.71 Draw the products of each acid–base reaction.

a. 

b. $(CH_3)_2CHCH_2CH_2COOH$ + Na_2CO_3 ⟶

17.72 Draw the products of each acid–base reaction.

a. 

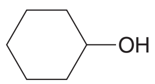
b. Cl_3CCOOH + $NaHCO_3$ ⟶

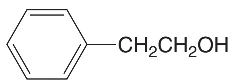
Formation of Esters and Amides

17.73 What ester is formed when butanoic acid ($CH_3CH_2CH_2CO_2H$) is treated with each alcohol in the presence of H_2SO_4?

a. CH_3OH

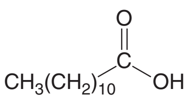
b. $CH_3CH_2CH_2OH$

c. 

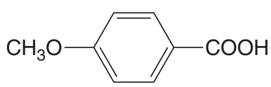
d. 

17.74 What ester is formed when each carboxylic acid is treated with 2-propanol [$(CH_3)_2CHOH$] in the presence of H_2SO_4?

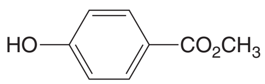
a. CH_3CH_2COOH

b. 

c. HCO_2H

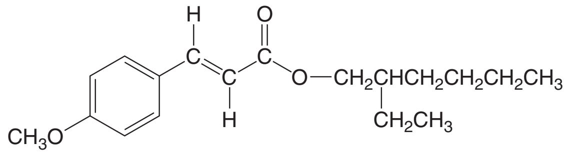
d. 

17.75 Methylparaben is a common preservative used in cosmetics. What carboxylic acid and alcohol are needed to synthesize methylparaben by Fischer esterification?



methylparaben

17.76 Octinoxate is the trade name for 2-ethylhexyl 4-methoxycinnamate, a widely used sunscreen. What carboxylic acid and alcohol are needed to synthesize octinoxate by Fischer esterification?



octinoxate

17.77 What amide is formed when butanoic acid ($CH_3CH_2CH_2CO_2H$) is heated with each nitrogen-containing compound?

a. NH_3

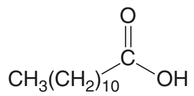
b. $CH_3CH_2NH_2$

c. $(CH_3CH_2)_2NH$

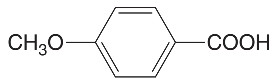
d. $CH_3NHCH_2CH_3$

17.78 What amide is formed when propylamine ($CH_3CH_2CH_2NH_2$) is heated with each carboxylic acid?

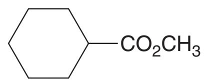
a. CH_3CH_2COOH

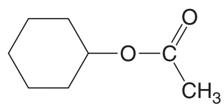
b. 

c. HCO_2H

d. 

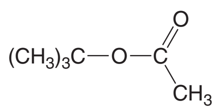
17.79 What carboxylic acid and alcohol are needed to synthesize each ester by Fischer esterification?

a. 

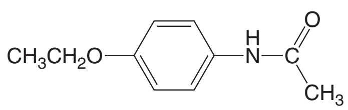
b. 

17.80 What carboxylic acid and alcohol are needed to synthesize each ester by Fischer esterification?

a. $(CH_3)_3CCO_2CH_3$

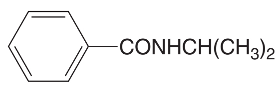
b. 

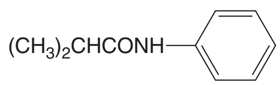
17.81 What carboxylic acid and amine are needed to synthesize the pain reliever phenacetin? Phenacetin was once a component of the over-the-counter pain reliever APC (aspirin, phenacetin, caffeine), but is no longer used because of its kidney toxicity.



phenacetin

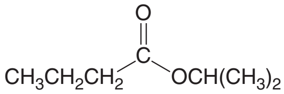
17.82 What carboxylic acid and amine are needed to synthesize each amide?

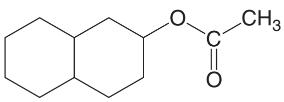
a. 

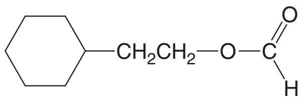
b. 

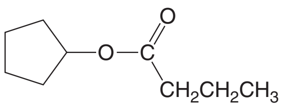
Hydrolysis

17.83 What products are formed when each ester is hydrolyzed with water and H_2SO_4?

a. 

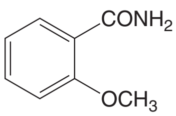
b. 

c. 

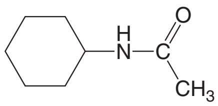
d. 

17.84 What products are formed when each ester in Problem 17.83 is hydrolyzed with water and NaOH?

17.85 What products are formed when each amide is hydrolyzed with water and HCl?

a. 

b. $(CH_3)_3CCON(CH_3)_2$

c. 

d. $HO(CH_2)_4CONHCH_3$

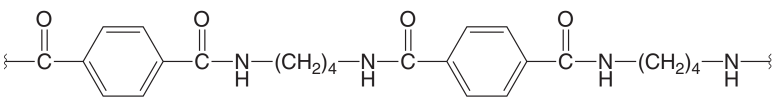
17.86 What products are formed when each amide in Problem 17.85 is hydrolyzed with water and NaOH?

17.87 Ethyl phenylacetate ($C_6H_5CH_2CO_2CH_2CH_3$) is a naturally occurring ester in honey. What hydrolysis products are formed when this ester is treated with water and H_2SO_4?

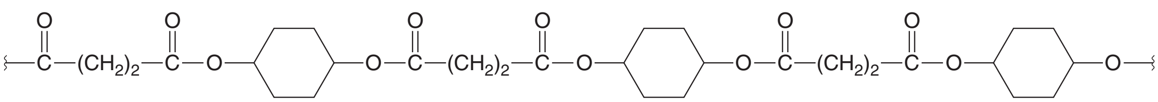
17.88 Benzyl acetate ($CH_3CO_2CH_2C_6H_5$) is a naturally occurring ester in peaches. What hydrolysis products are formed when this ester is treated with water and NaOH?

Polyesters and Polyamides

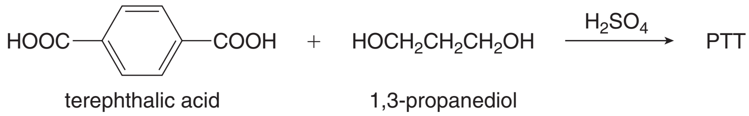
17.89 What dicarboxylic acid and diamine are needed to prepare the following polyamide?



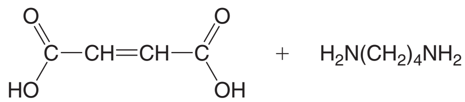
17.90 What dicarboxylic acid and diol are needed to form the following polyester?



17.91 PTT (polytrimethylene terephthalate) is a polyester formed from 1,3-propanediol ($HOCH_2CH_2CH_2OH$) by the given reaction. PTT is sold under the trade name Sorona by DuPont. 1,3-Propanediol can now be made from a plant source like corn, rather than from petroleum starting materials. This makes PTT a more environmentally friendly polyester than PET. What is the structure of PTT?



17.92 What polyamide is formed when the following dicarboxylic acid and diamine are heated together?

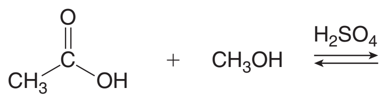


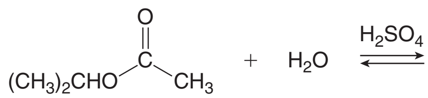
General Questions

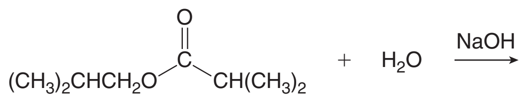
17.93 What is the difference between saponification and esterification?

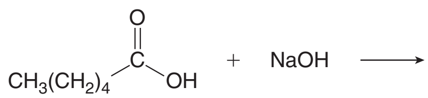
17.94 What is the difference between esterification and hydrolysis?

17.95 Draw the products formed in each reaction.

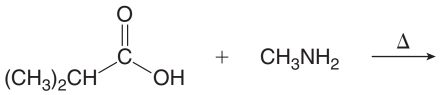
a. 

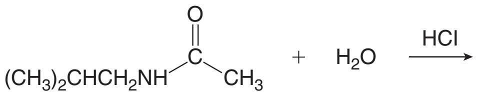
b. 

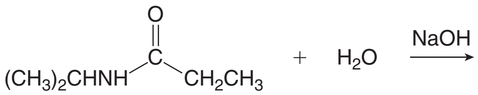
c. 

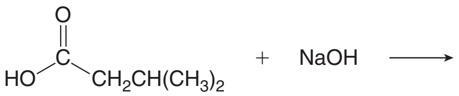
d. 

17.96 Draw the products formed in each reaction.

a. 

b. 

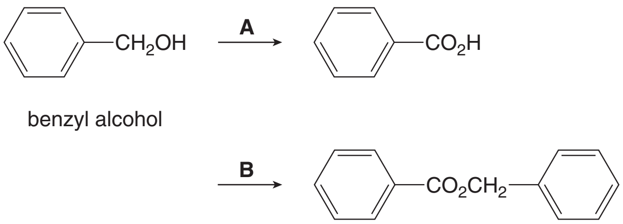
c. 

d. 

17.97 Answer the following questions about $(CH_3)_2CHCH_2CH_2CH_2CO_2H$ (**A**).
a. What is the IUPAC name for **A**?
b. Draw an isomer of **A** that has the same functional group.
c. Draw an isomer of **A** that has a different functional group.
d. What products are formed when **A** is treated with NaOH?
e. Predict the solubility properties of **A** in H_2O; in an organic solvent.
f. What product is formed when **A** is treated with CH_3CH_2OH and H_2SO_4?
g. What product is formed when **A** is heated with $CH_3CH_2NH_2$?

17.98 Answer the following questions about $(CH_3)_3C(CH_2)_6CO_2H$ (**B**).
a. What is the IUPAC name for **B**?
b. Draw an isomer of **B** that has the same functional group.
c. Draw an isomer of **B** that has a different functional group.
d. What products are formed when **B** is treated with NaOH?
e. Predict the solubility properties of **B** in H_2O; in an organic solvent.
f. What product is formed when **B** is treated with CH_3CH_2OH and H_2SO_4?
g. What product is formed when **B** is heated with $CH_3CH_2NH_2$?

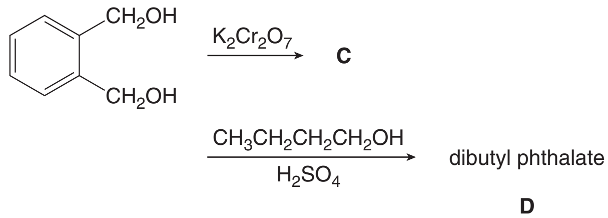
17.99 Identify **A** and **B** in the following two-step sequence that synthesizes benzyl benzoate from benzyl alcohol. Benzyl benzoate is a component of jasmine oil.



benzyl alcohol

benzyl benzoate

17.100 Dibutyl phthalate is a plasticizer added to make brittle polymers softer and more flexible. Dibutyl phthalate **(D)** can be prepared by the following two-step sequence. What are the structures of **C** and **D**?

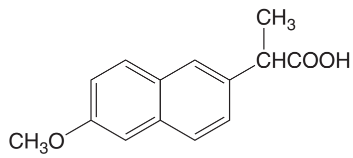


Applications

17.101 Which of the following structures represent soaps? Explain your answers.
a. $CH_3CO_2^-\ Na^+$
b. $CH_3(CH_2)_{14}CO_2^-\ Na^+$
c. $CH_3(CH_2)_{12}COOH$

17.102 Which of the following structures represent soaps? Explain your answers.
a. $CH_3CH_2CO_2^-\ K^+$
b. $CH_3(CH_2)_{16}COOH$
c. $CH_3(CH_2)_9CO_2^-\ Na^+$

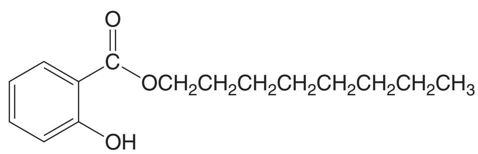
17.103 Like aspirin, naproxen contains a carboxyl group, so it undergoes similar acid–base reactions.



naproxen

a. Draw the reaction that occurs when naproxen is treated with NaOH.
b. What form of naproxen exists in the stomach?
c. What form of naproxen exists in the intestines?

17.104 Sunscreens that contain an ester can undergo hydrolysis. What products are formed when octyl salicylate, a commercial sunscreen, is hydrolyzed with water?



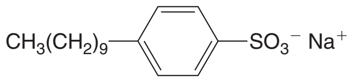
octyl salicylate

17.105 How does aspirin act as an anti-inflammatory agent?

17.106 What structural feature is important in making penicillin a biologically active antibiotic? How does the biological activity of penicillin come about?

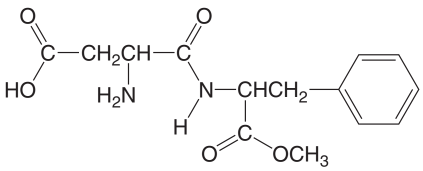
17.107 Explain how soap is able to dissolve nonpolar hydrocarbons in a polar solvent like H_2O.

17.108 Today, synthetic detergents like the compound drawn below are used to clean clothes, not soaps. Synthetic detergents are similar to soaps in that they contain an ionic head bonded to a large hydrocarbon group (the nonpolar tail). Explain how this detergent cleans away dirt.



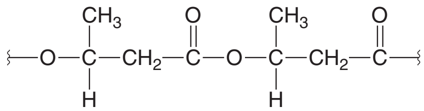
a detergent

17.109 Draw the products formed by acidic hydrolysis of **aspartame,** the artificial sweetener used in Equal and many diet beverages. One of the hydrolysis products of this reaction is the naturally occurring amino acid phenylalanine. Infants afflicted with phenylketonuria cannot metabolize this amino acid so it accumulates, causing mental retardation. When identified early, a diet limiting the consumption of phenylalanine (and compounds like aspartame that are converted to it) can allow for a normal life.



aspartame

17.110 Polyhydroxybutyrate (PHB) is a biodegradable polyester; that is, the polymer is degraded by microorganisms that naturally occur in the environment. Such biodegradable polymers are attractive alternatives to the commonly used polymers that persist in landfills for years. What is the single product formed when PHB is hydrolyzed with acid and water?



PHB

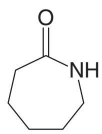
CHALLENGE QUESTIONS

17.111 Compounds that contain both a hydroxyl group (OH) and a carboxyl group (COOH) can undergo an intramolecular esterification reaction. What product is formed when each hydroxy acid undergoes an intramolecular reaction?

a. $HOCH_2CH_2CH_2CH_2CO_2H$

b. $HOCH_2CH_2CH_2CO_2H$

17.112 Lactams can be hydrolyzed with base, just like other amides. When a lactam is hydrolyzed, the ring is opened to form a product with two functional groups and no ring. What product is formed when caprolactam, the starting material for the synthesis of one type of nylon, is hydrolyzed with water and base?



caprolactam

18

CHAPTER OUTLINE

CHAPTER GOALS

In this chapter you will learn how to:

1. Identify the characteristics of amines
2. Name amines
3. Give examples of common alkaloids
4. Draw the products of acid–base reactions of amines
5. Identify and name ammonium salts
6. Discuss the function of neurotransmitters and explain how neurotransmitters and hormones differ
7. Discuss the role of dopamine and serotonin in the body
8. Give examples of important derivatives of 2-phenylethylamine
9. Discuss the chemistry of histamine, antihistamines, and anti-ulcer drugs



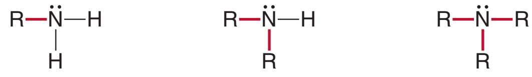
Tobacco products contain the addictive stimulant **nicotine,** an amine that is synthesized by tobacco plants as a defense against insect predators.

AMINES AND NEUROTRANSMITTERS

IN Chapter 18 we turn our attention to **amines,** organic compounds that contain nitrogen atoms. The amine nitrogen atom can be bonded to one, two, or three alkyl groups, and many amines have a nitrogen atom in a ring. All proteins contain amines, as do many vitamins and hormones. Many common amines, such as the caffeine in coffee and the nicotine in tobacco, are naturally occurring. Synthetic drugs used as sedatives, antihistamines, and bronchodilators also contain the amine functional group. Chapter 18 concludes with a discussion of **neurotransmitters,** important chemical messengers in the body, and many other related physiologically active amines.

18.1 STRUCTURE AND BONDING

***Amines* are organic nitrogen compounds,** formed by replacing one or more hydrogen atoms of ammonia (NH_3) with alkyl groups. Amines are classified as 1°, 2°, or 3° by the number of alkyl groups bonded to the *nitrogen* atom.



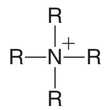
1° amine — 2° amine — 3° amine

Classifying amines as 1°, 2°, or 3° is reminiscent of classifying amides in Chapter 17, but is *different* from classifying alcohols and alkyl halides as 1°, 2°, and 3°. Compare, for example, a 2° amine and a 2° alcohol. A 2° amine (R_2NH) has *two* C—N bonds. A 2° alcohol (R_2CHOH) has only *one* C—O bond, but *two* C—C bonds on the carbon bonded to oxygen.

- **A primary (1°) amine has one C—N bond and the general structure RNH_2.**
- **A secondary (2°) amine has two C—N bonds and the general structure R_2NH.**
- **A tertiary (3°) amine has three C—N bonds and the general structure R_3N.**

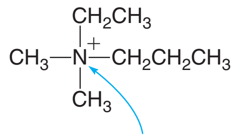
Like ammonia, **the amine nitrogen atom has a lone pair of electrons,** which is generally omitted in condensed structures. In Section 18.7, we will also learn about quaternary ammonium ions that contain a fourth alkyl group bonded to nitrogen. In this case, the nitrogen atom has no lone pair and bears a positive charge.

General structure



quaternary ammonium ion

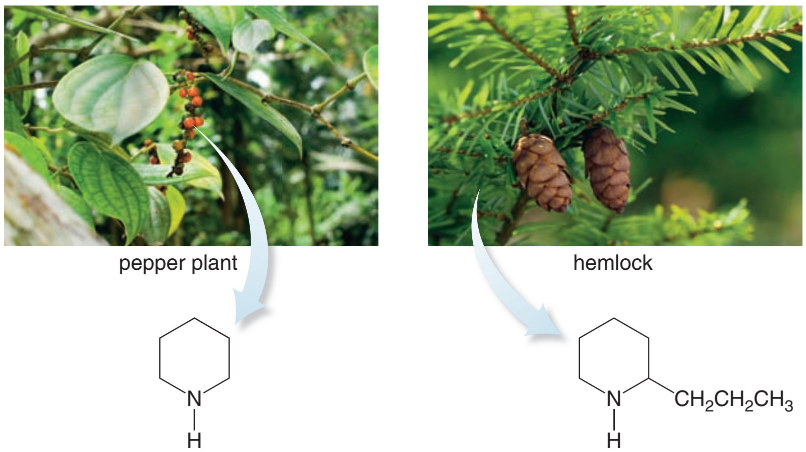
Example



N has no lone pair.

Recall from Section 14.7 that a ***heterocycle* is a ring that contains a heteroatom such as N, O, or S.**

The amine nitrogen atom can also be part of a ring to form a **heterocycle.** For example, piperidine, one compound isolated from black pepper, and coniine, the poisonous principle of hemlock, both contain a nitrogen atom in a six-membered ring.

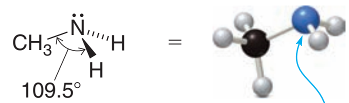


pepper plant — hemlock

piperidine — coniine

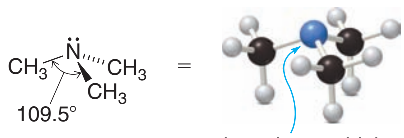
An amine nitrogen atom is surrounded by three atoms and one nonbonded electron pair, making it trigonal pyramidal in shape, with bond angles of approximately 109.5°.

CH_3NH_2 methylamine =



trigonal pyramidal

$(CH_3)_3N$ trimethylamine =



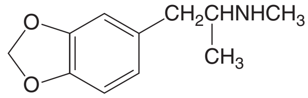
trigonal pyramidal

SAMPLE PROBLEM 18.1

Classify each amine in the following compounds as 1°, 2°, or 3°. Putrescine is partly responsible for the foul odor of decaying fish. MDMA is the illegal stimulant commonly called "Ecstasy."

a. $H_2N(CH_2)_4NH_2$

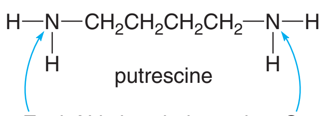
putrescine

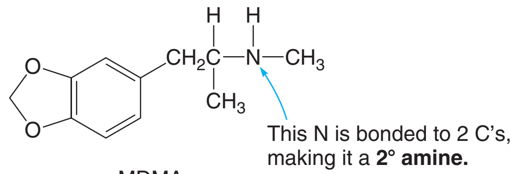
b. 

MDMA
"Ecstasy"

ANALYSIS To determine whether an amine is 1°, 2°, or 3°, count the number of carbons bonded to the nitrogen atom. A 1° amine has one C—N bond, and so forth.

SOLUTION Draw out the structure or add H's to the skeletal structure to clearly see how many C—N bonds the amine contains.

a. 

b. 

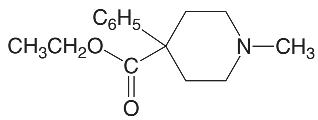
MDMA
"Ecstasy"

PROBLEM 18.1

Classify each amine in the following compounds as 1°, 2°, or 3°.

a. $H_2N(CH_2)_3NH(CH_2)_4NH(CH_2)_3NH_2$

spermine
(isolated from semen)

b. 

meperidine
(Trade name: Demerol)

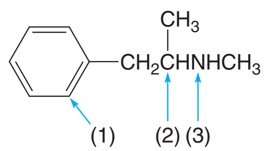
PROBLEM 18.2

Classify each amine in piperidine and coniine as 1°, 2°, or 3°.

Methamphetamine (Figure 18.1) is one of the many biologically active amines discussed in this chapter. Because it imparts to the user a pleasurable "high," methamphetamine is a widely abused illegal drug that has profound effects on the body and mind. Methamphetamine, known as speed, meth, or crystal meth, is highly addictive, easy to synthesize, and has adverse effects on the heart, lungs, blood vessels, and other organs. Prolonged use can lead to sleeplessness, seizures, hallucinations, paranoia, and serious heart disease.

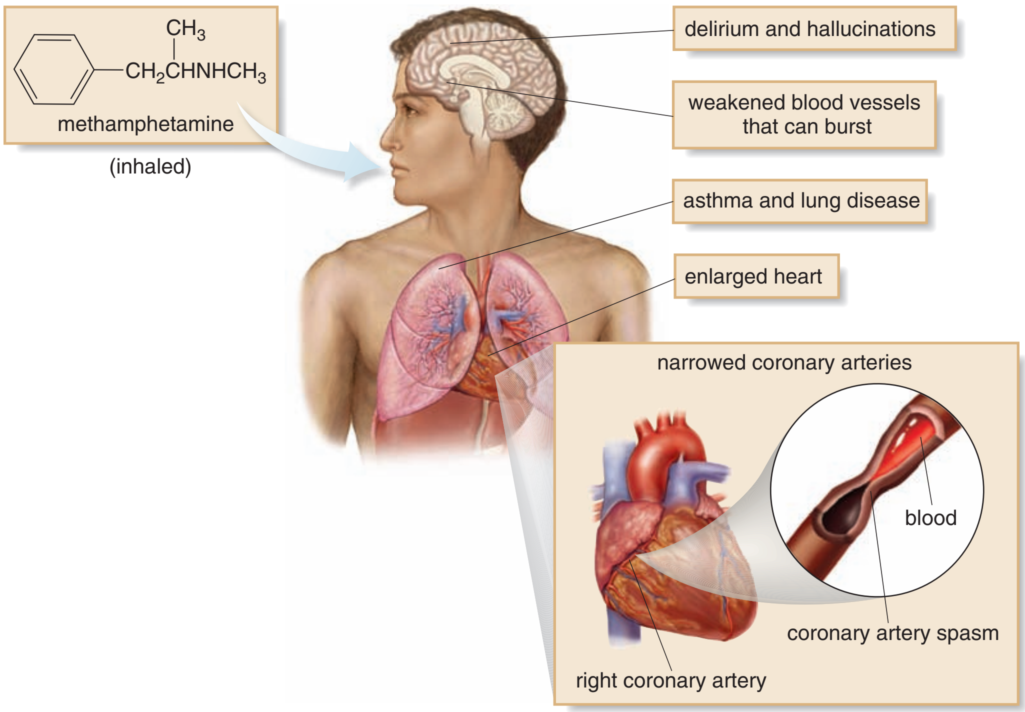
PROBLEM 18.3

(a) What type of amine does methamphetamine contain? (b) Give the molecular shape around each indicated atom in methamphetamine.



methamphetamine

FIGURE 18.1 Effects of Methamphetamine Use



Blood flow is constricted during an artery spasm, resulting in a heart attack.

18.2 NOMENCLATURE

18.2A PRIMARY AMINES

Primary (1°) amines are named using either systematic or common names. Systematic names can be used for any amine. To assign the **systematic name,** find the longest carbon chain bonded to the amine nitrogen, and change the ***-e*** ending of the parent alkane to the suffix ***-amine.*** Then use the usual rules of nomenclature to number the chain and name the substituents.

Common names are used only for simple amines. To assign a **common name,** name the alkyl group bonded to the nitrogen atom and add the suffix ***-amine,*** forming a single word.

CH_3NH_2
Common name: methylamine
Systematic name: methanamine

$CH_3CH_2CH_2CH_2NH_2$ (carbons numbered 4 3 2 1)
Common name: butylamine
Systematic name: 1-butanamine

18.2B SECONDARY AND TERTIARY AMINES

Secondary (2°) and 3° amines having identical alkyl groups are named by using the prefix **di-** or **tri-** with the name of the primary amine.

$CH_3CH_2—N(CH_2CH_3)—CH_2CH_3$
triethylamine

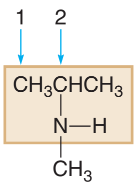
$CH_3CH_2CH_2—N(H)—CH_2CH_2CH_3$
dipropylamine

Secondary and tertiary amines having more than one kind of alkyl group are named as ***N*-substituted primary amines** using the following *How To* procedure.

HOW TO Name 2° and 3° Amines with Different Alkyl Groups

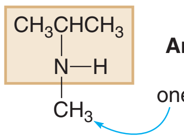
EXAMPLE **Name the following 2° amine: $(CH_3)_2CHNHCH_3$.**

Step [1] **Name the longest alkyl chain (or largest ring) bonded to the N atom as the parent amine.**



- Since the longest carbon chain has 3 C's, the parent name is *propanamine.*
- Since the N atom is bonded to the middle carbon, the name becomes *2-propanamine.*

Step [2] **Name the other groups on the N atom as alkyl groups, alphabetize the names when there is more than one substituent, and precede each name with the prefix *N*-.**



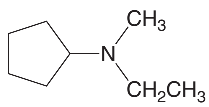
Answer: *N*-methyl-2-propanamine

one methyl substituent

SAMPLE PROBLEM 18.2

Give a systematic name for each amine.

a. $CH_3CH_2CH_2CH_2CH_2NH_2$

b. 

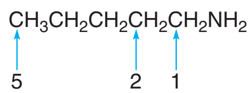
ANALYSIS AND SOLUTION

a. [1] For a 1° amine, find and name the longest chain containing the amine group.

$CH_3CH_2CH_2CH_2CH_2NH_2$

pentane ---→ penta*namine*
(5 C's)

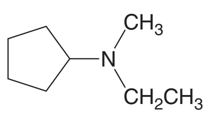
[2] Number the carbon skeleton.



You must use a number to show the location of the NH_2 group.
Answer: 1-pentanamine

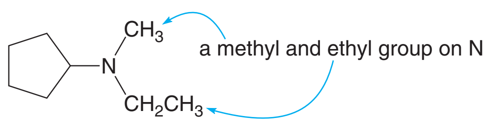
b. For a 3° amine, one alkyl group on N is the principal R group and the others are substituents.

[1] Name the ring bonded to the N.



5 C's in the ring
↓
cyclopentanamine

[2] Name the substituents.



- 2 N's are needed, one for each alkyl group.
- Alphabetize the *e* of **e**thyl before the *m* of **m**ethyl.

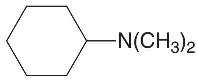
Answer: *N*-ethyl-*N*-methylcyclopentanamine

PROBLEM 18.4

Give an acceptable name for each amine.

a. $CH_3CH_2CHCH_3$ (with NH_2 on the third carbon)

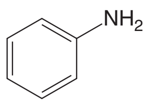
b. $CH_3CH_2CH_2NHCH_3$

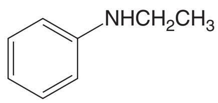
c. 

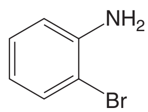
d. $(CH_3CH_2CH_2CH_2)_2NH$

18.2C AROMATIC AMINES

Aromatic amines, amines having a nitrogen atom bonded directly to a benzene ring, are named as derivatives of aniline.


aniline


N-ethylaniline


o-bromoaniline

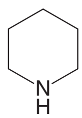
PROBLEM 18.5

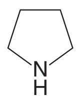
Draw a structure corresponding to each name: (a) *N*-methylaniline; (b) *m*-ethylaniline; (c) 3,5-diethylaniline; (d) *N,N*-diethylaniline.

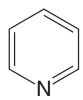
18.2D MISCELLANEOUS NOMENCLATURE FACTS

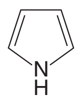
An $\mathbf{NH_2}$ group named as a substituent is called an **amino group.**

There are many different **nitrogen heterocycles,** and each ring type is named differently, depending on the number of N atoms in the ring and the ring size. The structures and names of four common nitrogen heterocycles are shown.


piperidine


pyrrolidine


pyridine


pyrrole

PROBLEM 18.6

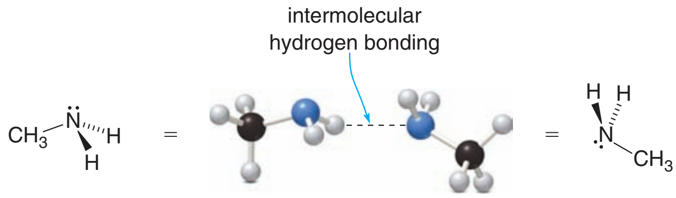
Draw a structure corresponding to each name.

a. 3-hexanamine
b. *N*-methylpentylamine
c. *p*-nitroaniline
d. *N*-methylpiperidine
e. *N,N*-dimethylethylamine
f. 2-aminocyclohexanone
g. 1-propylcyclohexanamine
h. *N*-propylaniline

18.3 PHYSICAL PROPERTIES

Many low molecular weight amines have *very* foul odors. **Trimethylamine** $[(CH_3)_3N]$, formed when enzymes break down certain fish proteins, has the characteristic odor of rotting fish. **Cadaverine** $(NH_2CH_2CH_2CH_2CH_2CH_2NH_2)$ is a poisonous diamine with a putrid odor also present in rotting fish, and partly responsible for the odor of semen, urine, and bad breath.

Because nitrogen is much more electronegative than carbon or hydrogen, amines contain polar C—N and N—H bonds. **Primary (1°) and 2° amines are also capable of intermolecular hydrogen bonding,** because they contain N—H bonds.



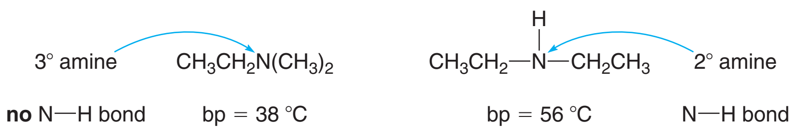
Since nitrogen is less electronegative than oxygen, however, intermolecular hydrogen bonds between N and H are *weaker* than those between O and H. As a result:

- **In comparing compounds of similar size, 1° and 2° amines have higher boiling points than compounds incapable of hydrogen bonding, but lower boiling points than alcohols that have stronger intermolecular hydrogen bonds.**

$CH_3CH_2OCH_2CH_3$	$CH_3CH_2CH_2CH_2NH_2$	$CH_3CH_2CH_2CH_2OH$
diethyl ether	1-butanamine	1-butanol
bp = 38 °C	bp = 78 °C	bp = 117 °C

Increasing intermolecular forces
Increasing boiling point

- **Tertiary (3°) amines have lower boiling points than 1° and 2° amines of comparable size, because they have no N—H bonds.**



higher boiling point

Amines are soluble in organic solvents regardless of size. Amines with fewer than six carbons are water soluble since they can hydrogen bond with water. Larger amines are water insoluble since the nonpolar alkyl portion is too large to dissolve in the polar water solvent.

SAMPLE PROBLEM 18.3

Which compound in each pair has the higher boiling point: (a) $CH_3CH_2NHCH_3$ or $CH_3CH_2OCH_3$; (b) $(CH_3)_3N$ or $CH_3CH_2CH_2NH_2$?

ANALYSIS

Keep in mind the general rule: For compounds of comparable size, **the stronger the intermolecular forces, the higher the boiling point.** Compounds that can hydrogen bond have higher boiling points than compounds that are polar but cannot hydrogen bond. Polar compounds have higher boiling points than nonpolar compounds.

SOLUTION

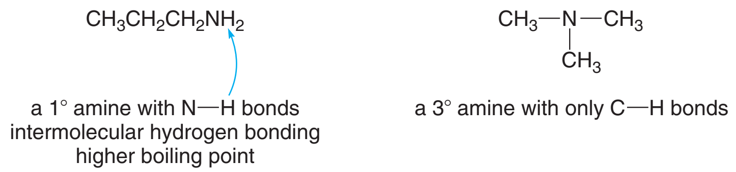
a. The 2° amine ($CH_3CH_2NHCH_3$) has an N—H bond, so intermolecular hydrogen bonding is possible. The ether ($CH_3CH_2OCH_3$) has only C—H bonds, so there is no possibility of intermolecular hydrogen bonding. $CH_3CH_2NHCH_3$ has a higher boiling point because it has stronger intermolecular forces.



a 2° amine with an N—H bond
intermolecular hydrogen bonding
higher boiling point

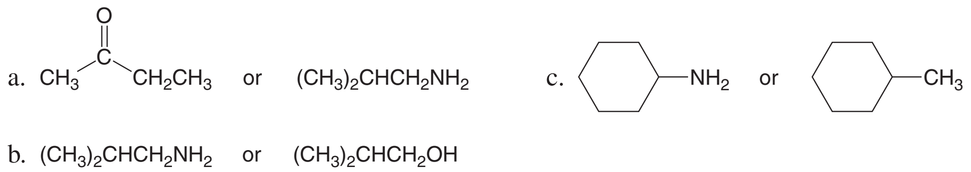
an ether with only C—H bonds

b. The 1° amine ($CH_3CH_2CH_2NH_2$) has N—H bonds, so intermolecular hydrogen bonding is possible. The 3° amine [$(CH_3)_3N$] has only C—H bonds, so there is no possibility of intermolecular hydrogen bonding. $CH_3CH_2CH_2NH_2$ has a higher boiling point because it has stronger intermolecular forces.



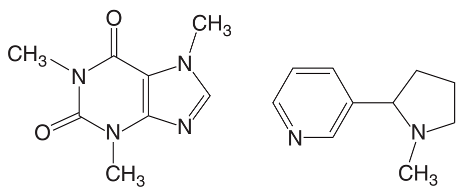
PROBLEM 18.7

Which compound in each pair has the higher boiling point?



18.4 FOCUS ON HEALTH & MEDICINE CAFFEINE AND NICOTINE

Caffeine and **nicotine** are widely used stimulants of the central nervous system that contain amine heterocycles. Caffeine and nicotine, like other amines discussed in Section 18.5, are ***alkaloids,*** **naturally occurring amines derived from plant sources.**



caffeine nicotine

18.4A CAFFEINE

CONSUMER NOTE



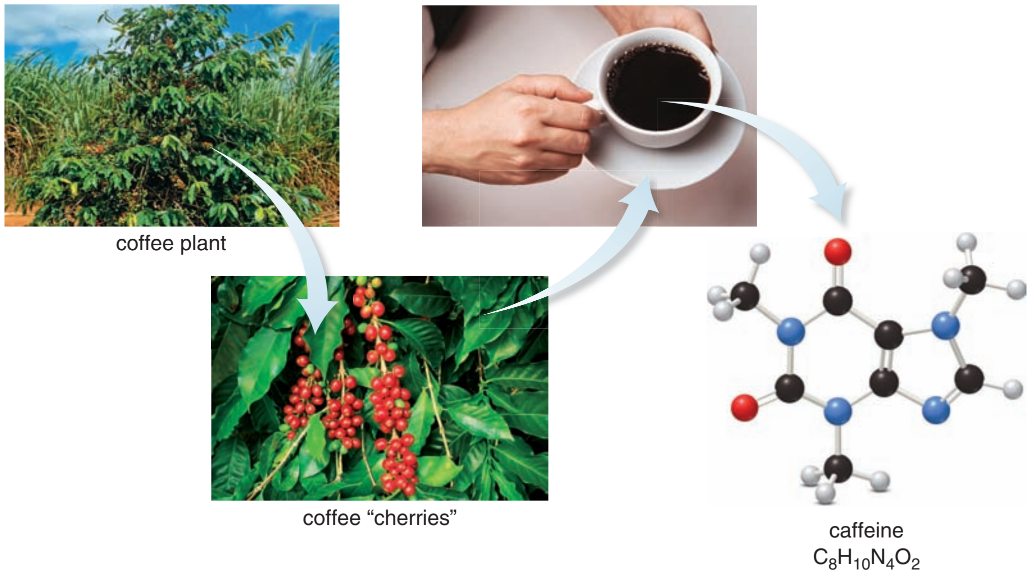
Some chocolate bars contain as much caffeine as a 12-oz can of cola.

Caffeine (Figure 18.2) is a bitter-tasting amine found in coffee and tea. Caffeine is also present in soft drinks and chocolate bars. The pain reliever Anacin contains aspirin and caffeine, and over-the-counter remedies like NoDoz used to ward off sleep contain caffeine. Table 18.1 lists the average caffeine content of several products.

Caffeine is a mild stimulant, usually imparting a feeling of alertness after consumption. It also increases heart rate, dilates airways, and stimulates the secretion of stomach acid. These effects are observed because caffeine increases glucose production, making an individual feel energetic. Caffeine's effects are temporary, so an individual must consume it throughout the day to maintain the same "high."

In moderation, caffeine consumption poses no health risks, but large quantities can cause insomnia, anxiety, and dehydration. Since caffeine is somewhat addicting, withdrawal symptoms—headache, irritability, and mild depression—can be observed when it is eliminated from the diet. Several studies suggest that pregnant women should limit their intake of caffeine, and that excessive caffeine consumption increases the risk of miscarriage. Nursing mothers are likewise advised to limit caffeine intake, since it passes into breast milk and can adversely affect newborn babies.

FIGURE 18.2 Caffeine—An Alkaloid from the Coffee Plant



Coffee is grown in 50 tropical countries worldwide, and ranks second only to oil in the amount traded internationally. The coffee "cherries" are picked by hand and dried to give two seeds per fruit. Raw beans are shipped to roasting facilities around the world.

TABLE 18.1 Average Caffeine Content in Common Foods and Drugs

Product	Serving Size	Caffeine (mg)
Coffee, brewed	8 oz	133
Coffee, instant	16 oz	47
Coffee, decaffeinated	8 oz	5
Tea, brewed	8 oz	53
Coca-Cola Classic	12 oz	35
Diet Coke	12 oz	47
Hershey's Chocolate Bar	1.55 oz	9
Hershey's Special Dark Chocolate	1.45 oz	31
Anacin	2 tablets	64
NoDoz	1 tablet	200

[Data taken from the web, Center for Science in the Public Interest.]

PROBLEM 18.8 Draw a complete structure of caffeine with all atoms and lone pairs.

PROBLEM 18.9 Decaffeinated coffee is produced by extracting the caffeine from coffee with a solvent. Initially dichloromethane (CH_2Cl_2) was used, but concerns arose over the ill health effects of trace amounts of CH_2Cl_2 remaining in the coffee. Why is caffeine soluble in CH_2Cl_2?

PROBLEM 18.10 What two types of nitrogen heterocycles are present in nicotine?

PROBLEM 18.11 Locate the single chirality center in nicotine. Draw both enantiomers of nicotine (see Section 15.4).

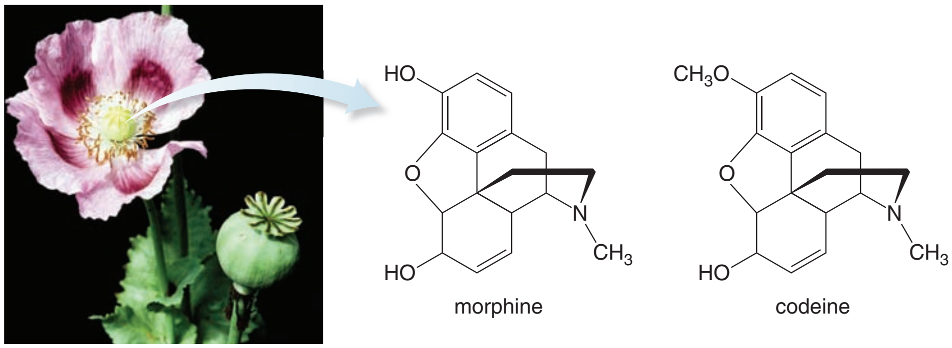
18.5 ALKALOIDS—AMINES FROM PLANT SOURCES

The word **alkaloid** is derived from the word *alkali,* since aqueous solutions of alkaloids are slightly basic.

Morphine, quinine, and **atropine** are three alkaloids with useful medicinal properties. All three compounds contain nitrogen heterocycles and have a complex structure with several functional groups.

18.5A MORPHINE AND RELATED ALKALOIDS

The psychological and analgesic effects of the opium poppy *Papaver somniferum* have been known for probably 6,000 years, and it has been widely used as a recreational drug and painkilling remedy for centuries. The analgesic and narcotic effects of opium are largely due to **morphine. Codeine,** an alkaloid of similar structure with a single methyl ether, is also present, but in much smaller amounts.



opium poppy

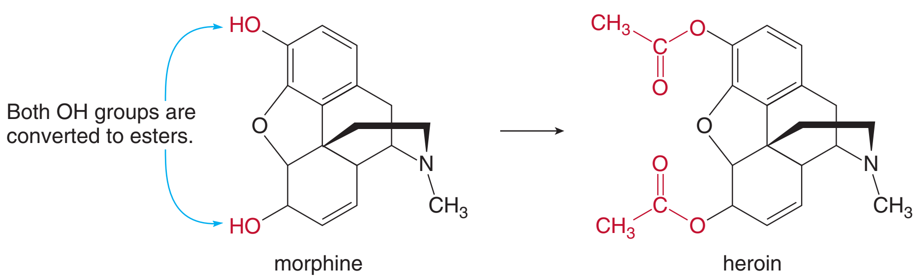
CONSUMER NOTE



Poppy seed tea, which contains morphine, was used as a folk remedy in parts of England until World War II. Since poppy seeds contain morphine, eating poppy seed cake or bagels can introduce enough morphine into the system to produce a positive test in a drug screen.

Morphine is especially useful in relieving severe chronic pain, so it is often prescribed for patients with terminal cancer. Morphine is also very addictive, and with time, higher doses are needed to produce the same effects. Approximately 95% of the morphine obtained from legally grown poppies is converted to codeine, a useful drug for the relief of less severe pain.

Heroin, a widely used, very addictive illicit drug, is readily prepared by converting the two hydroxyl groups of morphine to acetate esters. Heroin is less polar than morphine, making it more soluble in fat cells in the body. As a result, it is two to three times more potent than morphine in producing euphoria and pain relief.

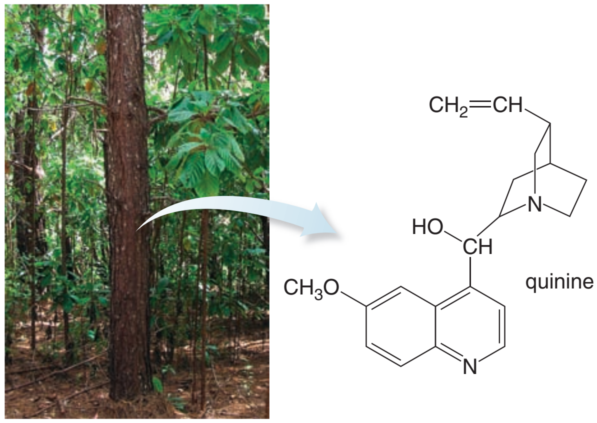


PROBLEM 18.12 Classify the amine in morphine as 1°, 2°, or 3°.

PROBLEM 18.13 Identify all the functional groups in heroin.

18.5B QUININE

Quinine is an alkaloid isolated from the bark of the cinchona tree native to the Andes Mountains. Quinine is a powerful antipyretic—that is, it reduces fever—and for centuries it was the only effective treatment for malaria. Its bitter taste gives tonic water its characteristic flavor.

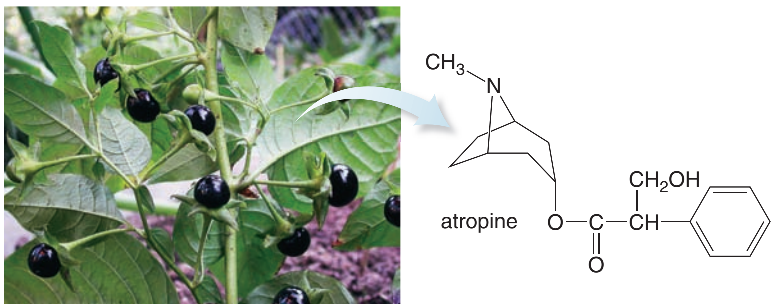


cinchona tree

PROBLEM 18.14 (a) How many trigonal planar carbon atoms does quinine contain? (b) How many tetrahedral carbon atoms does quinine contain?

18.5C ATROPINE

Atropine is an alkaloid isolated from *Atropa belladonna,* the deadly nightshade plant.



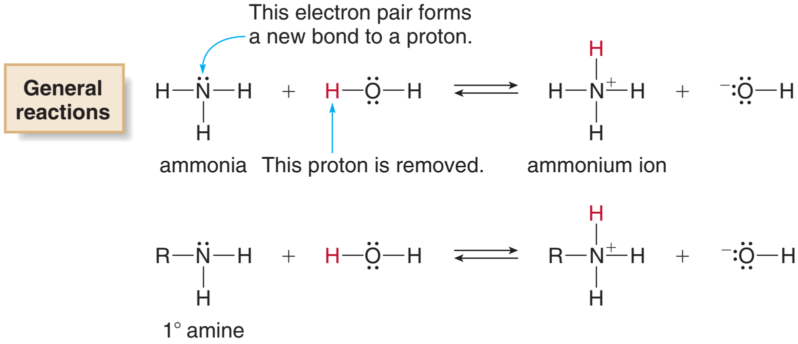
deadly nightshade plant

During the Renaissance (fourteenth to seventeenth centuries), women used the juice of the berries of the nightshade to enlarge the pupils of their eyes for cosmetic reasons. Sometimes ophthalmologists today use atropine to dilate pupils. Atropine also increases heart rate, so physicians administer atropine for this purpose. Atropine relaxes smooth muscles and interferes with nerve impulses. In higher doses atropine is toxic, leading to convulsions, coma, and death.

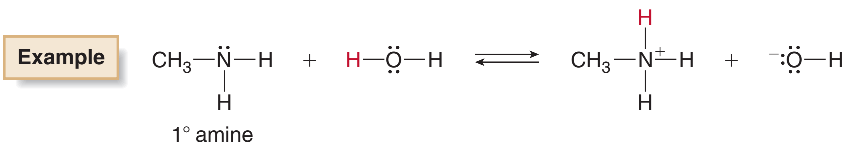
PROBLEM 18.15 Identify all of the functional groups in atropine, and classify the amine as 1°, 2°, or 3°.

18.6 AMINES AS BASES

Like ammonia (NH_3), **amines are bases;** that is, **they are *proton acceptors*.** When an amine is dissolved in water, an acid–base equilibrium occurs: the amine accepts a proton from H_2O, forming its conjugate acid, an **ammonium ion,** and water loses a proton, forming hydroxide, ^{-}OH.

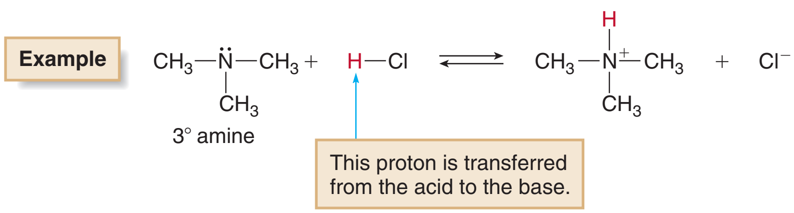


This acid–base reaction occurs with 1°, 2°, and 3° amines. While amines are more basic than other families of organic compounds, they are weak bases compared to inorganic bases like NaOH.



18.6A REACTION OF AMINES WITH ACIDS

Amines also react with acids such as HCl to form water-soluble salts. The lone pair of electrons from the amine nitrogen atom is always used to form a new bond to a proton from the acid.

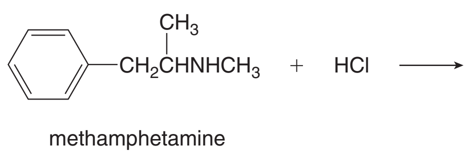


- The amine $[(CH_3)_3N]$ gains a proton to form its conjugate acid, an ammonium cation $[(CH_3)_3NH^+]$.
- A proton is removed from the acid (HCl) to form its conjugate base, the chloride anion (Cl^-).

Similar acid–base reactions occur with other inorganic acids (H_2SO_4), and with organic acids like CH_3COOH, as well. **In each reaction, the amine gains a proton and the acid loses a proton.** This fundamental reaction of amines occurs no matter how complex the amine, as shown in Sample Problem 18.4.

- In an acid–base reaction of an amine, the amine nitrogen always forms a new bond to a proton forming an ammonium ion.

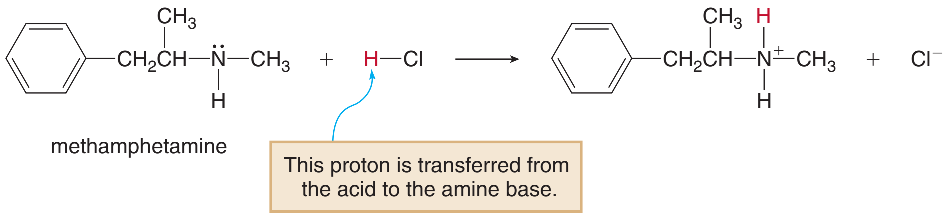
SAMPLE PROBLEM 18.4 What products are formed when methamphetamine (Section 18.1) reacts with HCl?



ANALYSIS In any acid–base reaction with an amine:

- Locate the N atom of the amine and add a proton to it. Since the amine nitrogen is neutral to begin with, adding a proton gives it a +1 charge.
- Remove a proton from the acid (HCl) and form its conjugate base (Cl^-).

SOLUTION Transfer a proton from the acid to the base. Use the lone pair on the N atom to form the new bond to the proton of the acid.



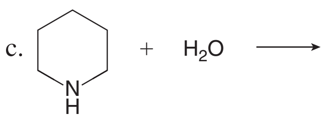
Thus, HCl loses a proton to form Cl^-, and the N atom of amphetamine gains a proton to form an ammonium cation.

PROBLEM 18.16 What products are formed when each of the following amines is treated with HCl: (a) $CH_3CH_2NH_2$; (b) $(CH_3CH_2)_2NH$; (c) $(CH_3CH_2)_3N$?

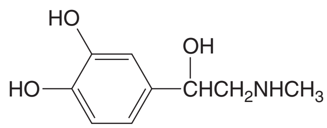
PROBLEM 18.17 Draw the products of each acid–base reaction.

a. $CH_3CH_2CH_2CH_2{-}NH_2 + HCl \longrightarrow$

b. $(CH_3)_2NH + C_6H_5COOH \longrightarrow$

c. 

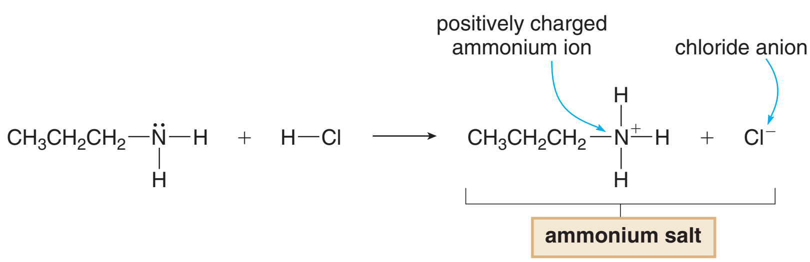
PROBLEM 18.18 What products are formed when epinephrine is treated with H_2SO_4?



epinephrine
(adrenaline)

18.6B AMMONIUM SALTS

When an amine reacts with an acid, the product is an ***ammonium salt:*** **the amine forms a positively charged ammonium ion and the acid forms an anion.**



To name an ammonium salt, change the suffix *-amine* of the parent amine from which the salt is formed to the suffix *-ammonium.* Then add the name of the anion. Two examples are shown in Sample Problem 18.5.

SAMPLE PROBLEM 18.5

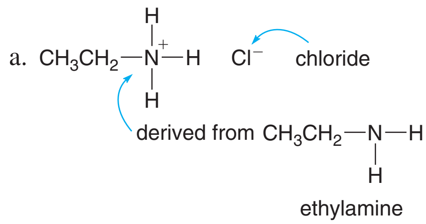
Name each ammonium salt.

a. $CH_3CH_2\overset{+}{N}H_3$ Cl^- b. $(CH_3)_3\overset{+}{N}H$ CH_3COO^-

ANALYSIS To name an ammonium salt, draw out the four groups bonded to the N atom. Remove one hydrogen from the N atom to draw the structure of the parent amine. Then put the two parts of the name together.

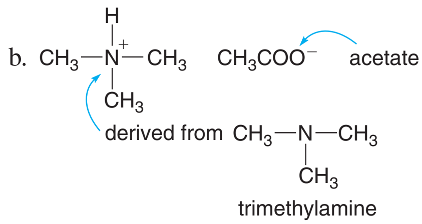
- Name the ammonium ion by changing the suffix *-amine* of the parent amine to the suffix *-ammonium.*
- Add the name of the anion.

SOLUTION



- Change the name ethyl*amine* to ethyl*ammonium.*
- Add the name of the anion, chloride.

Answer: ethylammonium chloride



- Change the name trimethyl*amine* to trimethyl*ammonium.*
- Add the name of the anion, acetate.

Answer: trimethylammonium acetate

PROBLEM 18.19

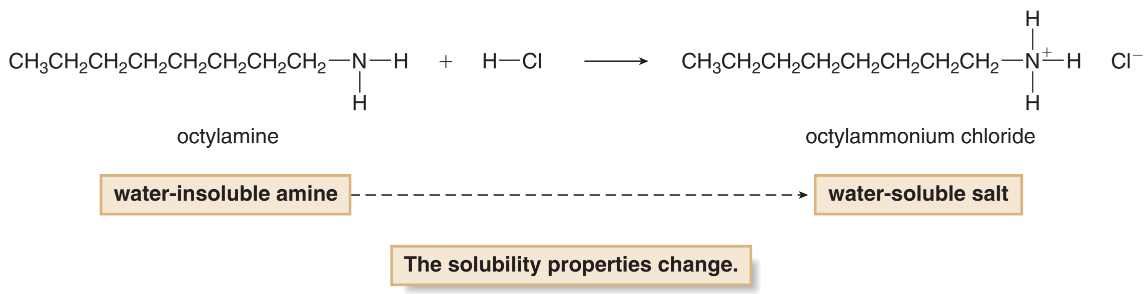
Name each ammonium salt.

a. $CH_3\overset{+}{N}H_3$ Cl^- b. $(CH_3CH_2CH_2)_2\overset{+}{N}H_2$ Br^- c. $(CH_3)_2\overset{+}{N}HCH_2CH_3$ CH_3COO^-

Ammonium salts are ionic compounds, and as a result:

- **Ammonium salts are water-soluble solids.**

In this way, the solubility properties of an amine can be changed by treatment with acid. For example, octylamine has eight carbons, making it water insoluble. Reaction with HCl forms octylammonium chloride. This ionic solid is now soluble in water.



- **A water-insoluble amine can be converted to a water-soluble ammonium salt by treatment with acid.**

18.4B NICOTINE

Nicotine (Figure 18.3) is a highly toxic amine isolated from tobacco. In small doses it acts as a stimulant, but in larger doses causes depression, nausea, and even death. Nicotine is synthesized in tobacco plants as a defense against insect predators, and is used commercially as an insecticide.

Although inhaled tobacco smoke contains over 4,000 compounds, many of which are toxic or cancer causing, nicotine is the compound that makes smoking addictive. Nicotine imparts a sense of pleasure to the smoker, and once a smoker is "hooked," an individual needs to continue smoking to avoid the extreme discomforts of withdrawal—restlessness, anxiety, and craving.

Cigarette smoking causes lung disease, heart disease, and cancer, and it is recognized today as the leading cause of avoidable death in the United States. Despite this well known fact, the nicotine addiction makes it difficult for current smokers to quit. In fact, the sale of nicotine-free cigarettes many years ago was an unsuccessful enterprise because the nicotine in cigarettes is what smokers really crave when they light up.

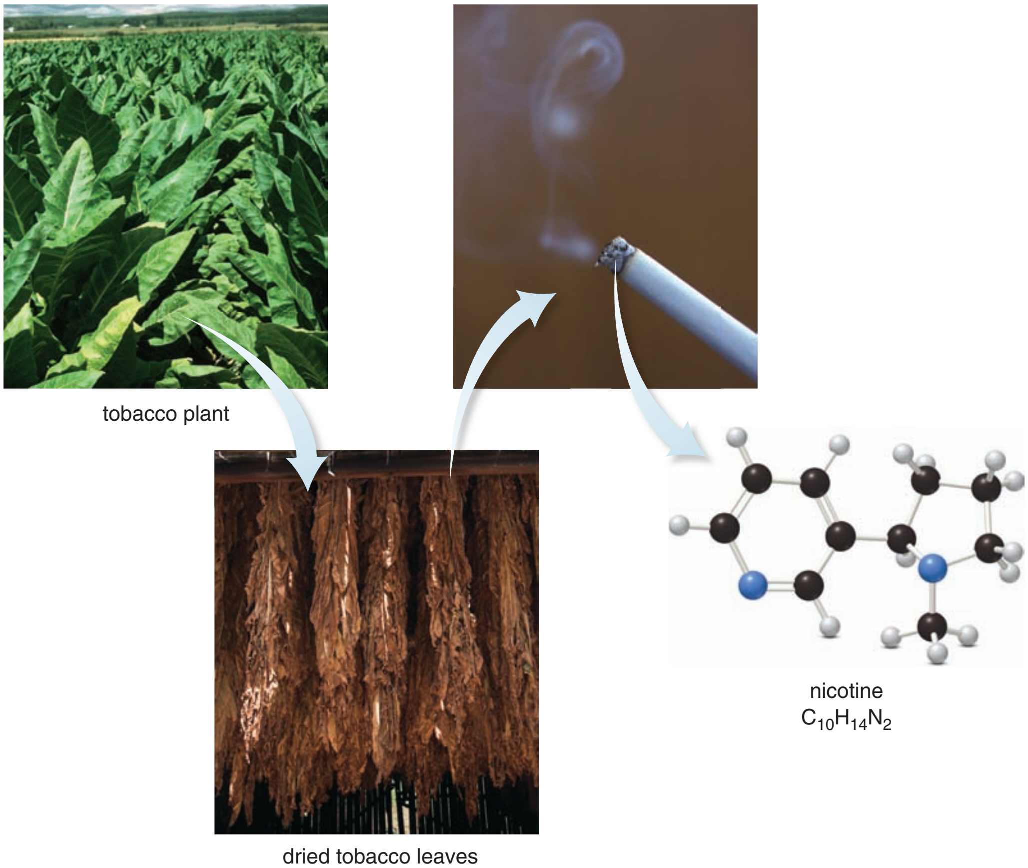
One method employed by some to quit smoking involves the use of a nicotine patch. The patch is applied to the skin and nicotine diffuses through the skin and into the bloodstream. In this way, a smoker still derives pleasure from the nicotine in the system, but is no longer exposed to the ill effects of the other components of cigarette smoke. Slowly the concentration of nicotine in the patch is reduced, with the hope that eventually the smoker will no longer need nicotine. A similar strategy is used with chewing gum that contains nicotine.

HEALTH NOTE



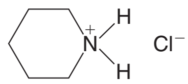
Nicotine patches and nicotine-containing chewing gum have been effectively used by many individuals to quit smoking.

FIGURE 18.3 Nicotine—An Alkaloid from the Tobacco Plant

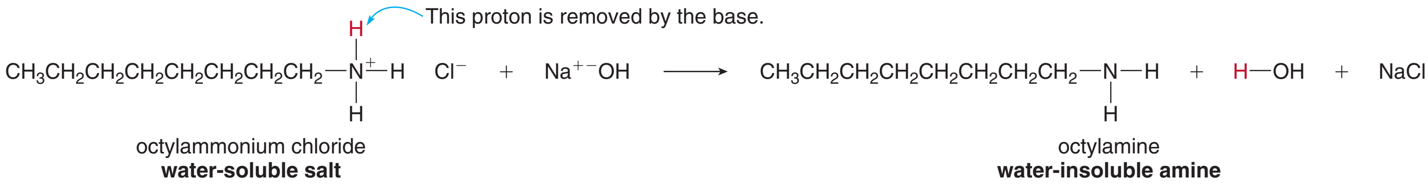


Tobacco is grown in temperate climates. The leaves are harvested and dried, and then converted to cigarettes and other tobacco products.

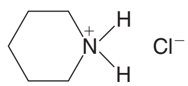
PROBLEM 18.20 Label each compound as water soluble or water insoluble.

a. $(CH_3CH_2)_3N$ b. $(CH_3CH_2)_3\overset{+}{N}H$ Br^- c. $CH_3CH_2NH_2$ d. 

Ammonium salts can be re-converted to amines by treatment with base. Base removes a proton from the nitrogen atom of the amine, regenerating the neutral amine.



PROBLEM 18.21 What product is formed when each ammonium salt is treated with NaOH?

a. $(CH_3CH_2)_3\overset{+}{N}H$ Br^- b. $CH_3CH_2\overset{+}{N}H_3$ HSO_4^- c. 

18.7 FOCUS ON HEALTH & MEDICINE AMMONIUM SALTS AS USEFUL DRUGS

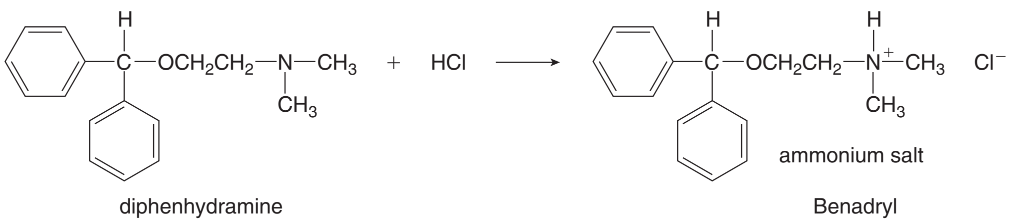
CONSUMER NOTE



Many antihistamines and decongestants are sold as their hydrochloride salts.

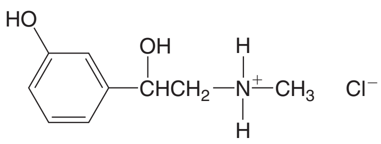
Many amines with useful medicinal properties are sold as their ammonium salts. Since the ammonium salts are more water soluble than the parent amine, they are easily transported through the body in the aqueous medium of the blood.

For example, diphenhydramine is a 3° amine that is sold as its ammonium salt under the name of Benadryl. Benadryl, formed by treating diphenhydramine with HCl, is an over-the-counter antihistamine that is used to relieve the itch and irritation of skin rashes and hives.

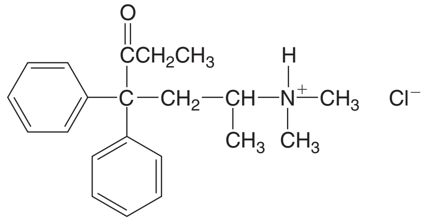


Medicines sold as ammonium salts are often derived from the names of the amine and the acid used to form them. Since Benadryl is formed from diphenhydramine and HCl, it is called **diphenhydramine hydrochloride.**

Two other examples of amines sold as their ammonium salts are phenylephrine hydrochloride, the decongestant in Sudafed PE, Theraflu, and DayQuil, and methadone hydrochloride, a long-acting narcotic taken orally to treat chronic painful conditions. Methadone hydrochloride is also used as a substitute narcotic for heroin addicts.

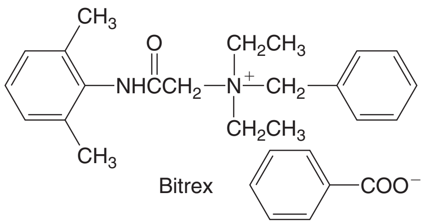


phenylephrine hydrochloride
(decongestant in Sudafed PE,
Theraflu, and DayQuil)

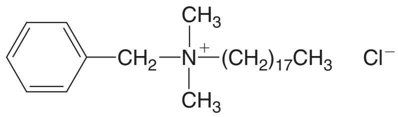


methadone hydrochloride
(narcotic analgesic)

Some **quaternary ammonium salts** (R_4N^+ X^-, Section 18.1)—that is, ammonium salts with nitrogen atoms bonded to *four* alkyl groups—are also useful agents. Bitrex is a foul-tasting nontoxic salt used on children's fingers to keep them from biting their nails or sucking their thumbs. Benzalkonium chloride is a disinfectant and antiseptic in mouthwash.



Bitrex



benzalkonium chloride

PROBLEM 18.22 Draw the structures of the amines from which phenylephrine hydrochloride and methadone hydrochloride are derived.

PROBLEM 18.23 When Benadryl is treated with a base like NaOH, the free amine, diphenhydramine, is re-formed, as we learned in Section 18.6. Explain why a similar reaction does not occur with a quaternary ammonium salt like Bitrex.

18.8 NEUROTRANSMITTERS

A *neurotransmitter* is a chemical messenger that transmits nerve impulses from one nerve cell—neuron—to another cell. As shown in Figure 18.4, a neuron consists of many short filaments called **dendrites** connected to a cell body. A long stem called an **axon** also protrudes from the cell body. The axon ends in numerous small filaments at its opposite end. These filaments are separated from the dendrites of a nearby neuron by a small gap called the **synapse.**

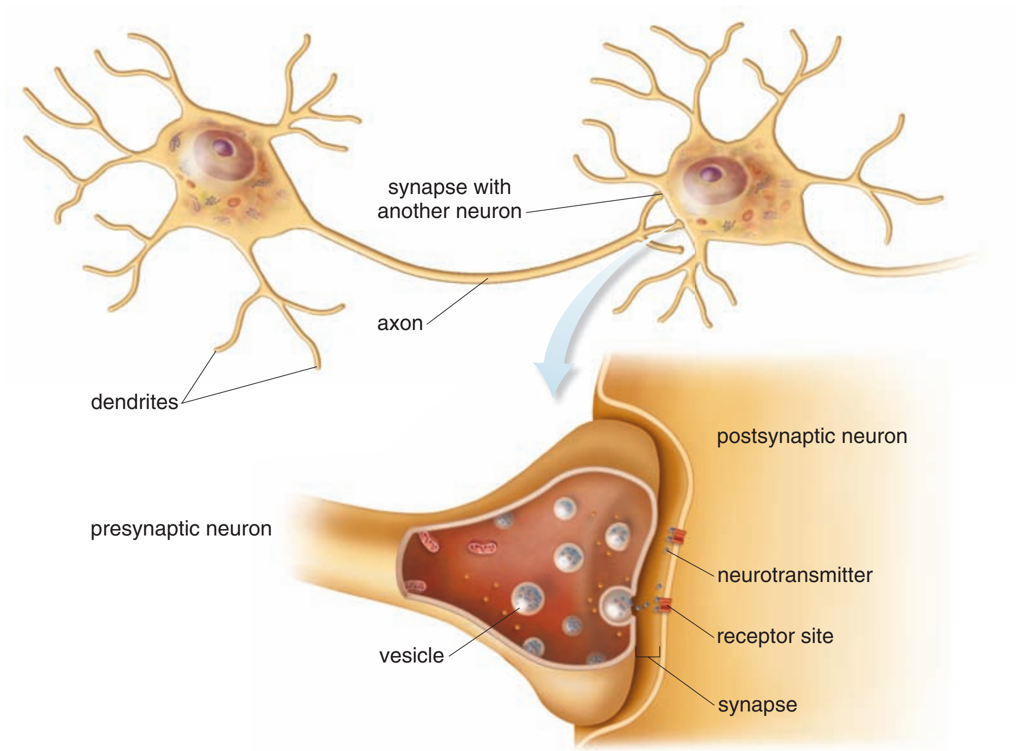
Neurotransmitters are stored in small packets called **vesicles** in the filaments of the axon near the synapse. When an electrical signal flows from the cell body of the neuron along the axon to the filaments, the neurotransmitter is released, diffuses across the synapse, and binds to a receptor on the dendrites of an adjacent neuron.

- **The presynaptic neuron releases the neurotransmitter.**
- **The postsynaptic neuron contains the receptors that bind the neurotransmitter.**

Once the neurotransmitter is bound to the receptor, the chemical message is delivered. The neurotransmitter is then degraded or it is returned to the presynaptic neuron to begin the process again.

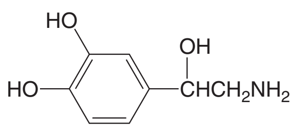
Drugs may be used to affect neurotransmitters in many different ways. Some drugs prevent the release of a neurotransmitter or prevent its binding to a receptor. Other drugs increase the amount of neurotransmitter released. Some drugs affect the degradation of a neurotransmitter or prevent its reuptake by the presynaptic neuron.

FIGURE 18.4 Neurotransmitters—Transmitting Information Between Neurons

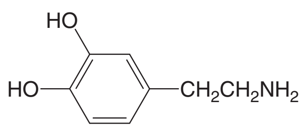


Neurotransmitters are released from vesicles in the presynaptic neuron and diffuse through the synapse to bind to the receptor sites on the postsynaptic neuron.

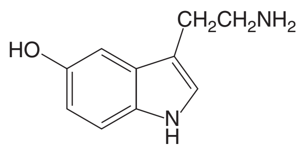
All neurotransmitters contain nitrogen atoms. Three important neurotransmitters are amines—**norepinephrine, dopamine,** and **serotonin**—and one is an ammonium ion—**acetylcholine.**



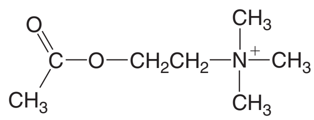
norepinephrine
(noradrenaline)



dopamine



serotonin

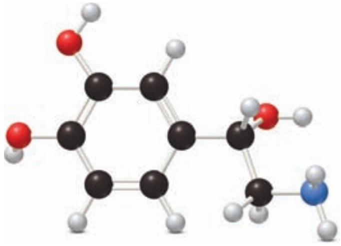


acetylcholine

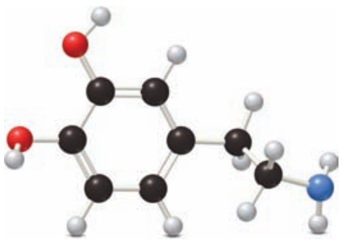
18.8A NOREPINEPHRINE AND DOPAMINE

Norepinephrine, commonly called **noradrenaline,** and **dopamine** are two structurally related neurotransmitters that are both synthesized from the amino acid tyrosine, as shown in Figure 18.5.

Proper levels of both amines are needed for good mental health. For example, when **norepinephrine** levels are above normal, an individual feels unusually elated, and very high levels are associated with manic behavior. Norepinephrine is also converted to adrenaline when an individual experiences fear or stress, as we will learn in Section 18.9.

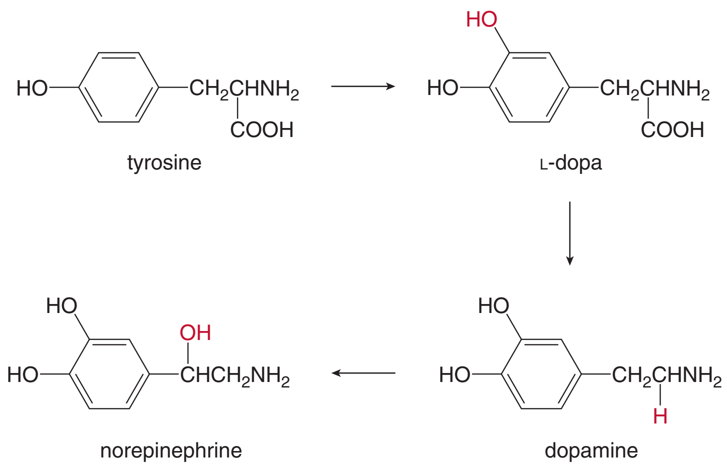


norepinephrine



dopamine

FIGURE 18.5 Synthesis of Norepinephrine and Dopamine



Norepinephrine and dopamine are both synthesized from the amino acid tyrosine by a multistep route. The newly introduced group at each stage is shown in red.

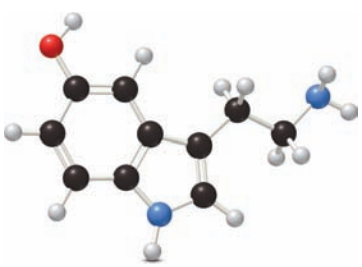
Dopamine affects brain processes that control movement, emotions, and pleasure. When dopamine-producing neurons die and there is too little dopamine in the brain, an individual loses control of fine motor skills and Parkinson's disease results. As we learned in Section 15.5, the level of dopamine in the brain cannot be increased simply by giving an individual dopamine, because dopamine does not cross the blood–brain barrier. L-Dopa, a precursor of dopamine shown in Figure 18.5, can travel from the bloodstream to the brain, so it is an effective treatment for Parkinson's disease. Elevated dopamine levels are also unhealthy and are associated with schizophrenia.

Dopamine plays an important role in addiction. Normal dopamine levels give an individual a pleasurable, satisfied feeling. Increased levels result in an intense "high." Drugs such as heroin, cocaine, and alcohol increase dopamine levels. When dopamine receptors are stimulated more than normal, the number and sensitivity of the receptors decreases, and an individual requires more of a drug to feel the same sense of pleasure.

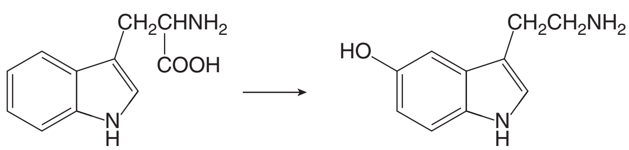
PROBLEM 18.24 Indicate the chirality center in each of the compounds in Figure 18.5. Which compounds are achiral and contain no chirality centers?

18.8B SEROTONIN

The neurotransmitter **serotonin** is synthesized from the amino acid tryptophan. Serotonin plays an important role in mood, sleep, perception, and temperature regulation. We get sleepy after eating a turkey dinner on Thanksgiving because the unusually high level of tryptophan in turkey is converted to serotonin.

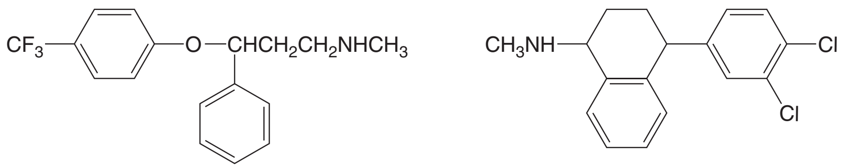


serotonin



tryptophan serotonin

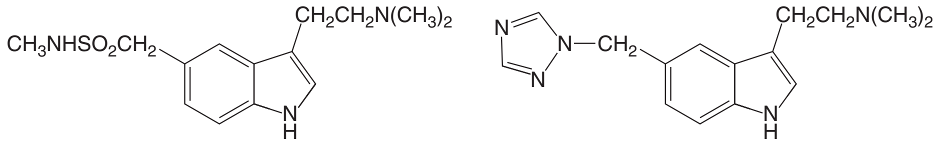
A deficiency of serotonin causes depression. Understanding the central role of serotonin in determining one's mood has led to the development of a wide variety of drugs for the treatment of depression. The most widely used antidepressants today are **selective serotonin reuptake inhibitors (SSRIs).** These drugs act by inhibiting the reuptake of serotonin by the presynaptic neuron, thus effectively increasing its concentration. Fluoxetine (trade name: Prozac) and sertraline (trade name: Zoloft) are two common antidepressants that act in this way.



fluoxetine
(Trade name: Prozac)

sertraline
(Trade name: Zoloft)

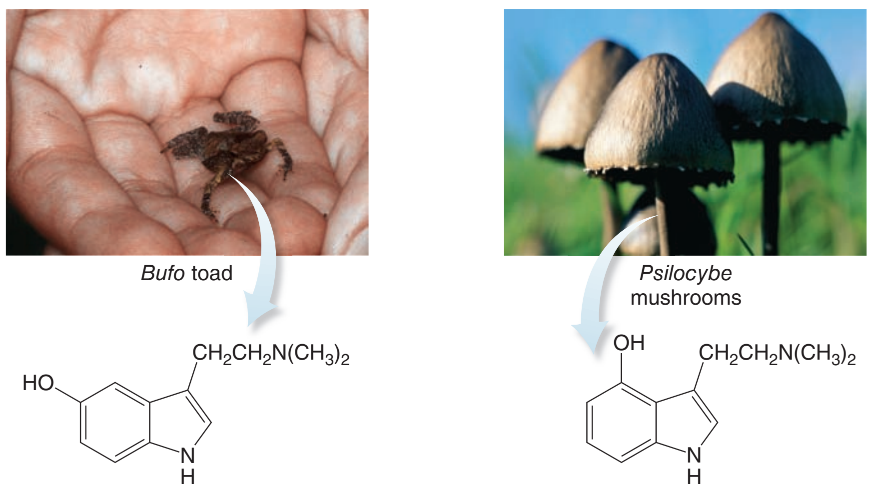
The discovery that migraine headaches result from improper levels of serotonin in the brain has led to the synthesis of several drugs that combat the pain, nausea, and light sensitivity that are associated with this condition. These drugs include sumatriptan (trade name: Imitrex) and rizatriptan (trade name: Maxalt).



sumatriptan
(Trade name: Imitrex)

rizatriptan
(Trade name: Maxalt)

Drugs that interfere with the metabolism of serotonin have a profound effect on mental state. For example, bufotenin, isolated from *Bufo* toads from the Amazon jungle, and psilocin isolated from *Psilocybe* mushrooms, are very similar in structure to serotonin and both cause intense hallucinations.



bufotenin

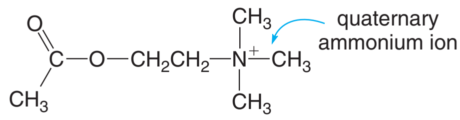
psilocin

PROBLEM 18.25 The conversion of tryptophan to serotonin is a two-step process. What functional groups must be added or removed during this process?

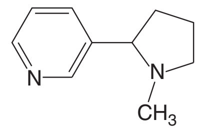
PROBLEM 18.26 How are serotonin, bufotenin, and psilocin similar in structure? Classify the amines in these three compounds as 1°, 2°, or 3°.

18.8C ACETYLCHOLINE AND NICOTINE ADDICTION

Acetylcholine is a quaternary ammonium ion that serves as a neurotransmitter between neurons and muscle cells. In the brain, acetylcholine is involved in memory, mood, and other functions.



acetylcholine



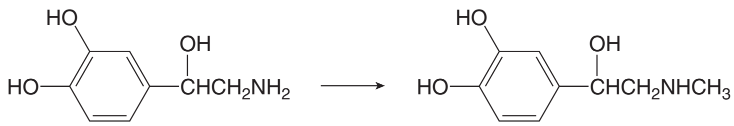
nicotine

The pleasurable high that a smoker feels is due to nicotine interacting with acetylcholine receptors. At low concentrations, nicotine is a stimulant because it binds to these receptors, resulting in a feeling of well-being and alertness. Other nerve cells are also activated and this releases dopamine. The sense of pleasure resulting from the release of dopamine is what causes nicotine to be addictive. Over time receptors are inactivated and some degenerate, so tolerance to nicotine develops and larger quantities are needed to maintain the same sense of pleasure.

18.9 FOCUS ON THE HUMAN BODY EPINEPHRINE AND RELATED COMPOUNDS

While neurotransmitters are the chemical messengers of the nervous system, **hormones** are the chemical messengers of the endocrine system. **A *hormone* is a compound produced by an endocrine gland, which then travels through the bloodstream to a target tissue or organ.**

Epinephrine, or **adrenaline** as it is commonly called, is a hormone synthesized in the adrenal glands from norepinephrine (noradrenaline).

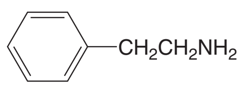


norepinephrine (noradrenaline) → epinephrine (adrenaline)

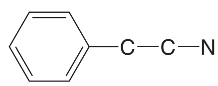
When an individual senses danger or is confronted by stress, the hypothalamus region of the brain signals the adrenal glands to synthesize and release epinephrine, which enters the bloodstream and then stimulates a response in many organs (Figure 18.6). Stored carbohydrates are metabolized in the liver to form glucose, which is further metabolized to provide an energy boost. Heart rate and blood pressure increase, and lung passages are dilated. These physiological changes are commonly referred to as a "rush of adrenaline," and they prepare an individual for "fight or flight."

18.9A DERIVATIVES OF 2-PHENYLETHYLAMINE

Like epinephrine and norepinephrine, a large number of physiologically active compounds are derived from **2-phenylethylamine, $C_6H_5CH_2CH_2NH_2$.** Each of these compounds has a common structural unit: a benzene ring bonded to a two-carbon chain that is bonded to a nitrogen atom.



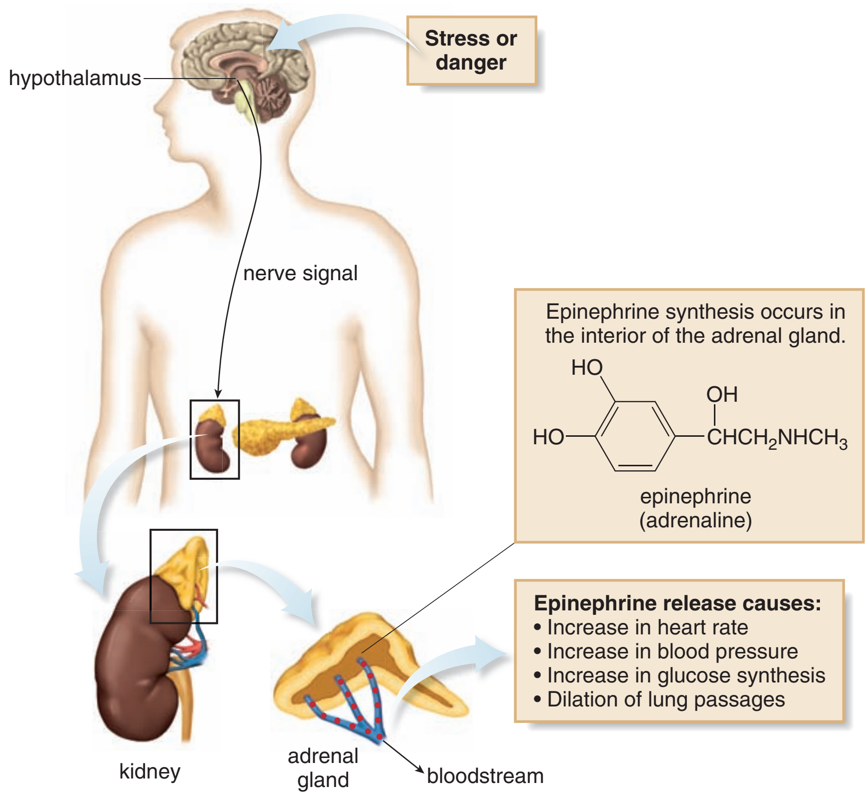
2-phenylethylamine



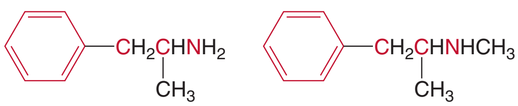
common structural feature

For example, **amphetamine** and **methamphetamine** are derivatives of 2-phenylethylamine that are powerful stimulants of the central nervous system. Both amines increase heart rate and

FIGURE 18.6 Epinephrine—The "Fight or Flight" Hormone



respiratory rate. Since they increase glucose concentration in the bloodstream, they decrease hunger and fatigue. While amphetamine and methamphetamine may be prescribed for attention deficit hyperactivity disorder (ADHD) and weight reduction under the trade names Adderall and Desoxyn, respectively, they are highly addictive and widely abused drugs that must be used with extreme care. Both amphetamine and methamphetamine increase the level of dopamine in the brain, causing a pleasurable "high."

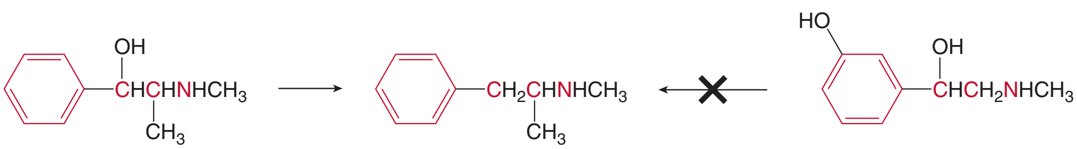


amphetamine methamphetamine

The atoms of 2-phenylethylamine are shown in red.



Pseudoephedrine, the decongestant in Sudafed, is another derivative of 2-phenylethylamine. Since pseudoephedrine can be readily converted to methamphetamine, it has been replaced in many products by a related amine, **phenylephrine.** For example, Pfizer markets its pseudoephedrine-free decongestant as Sudafed PE. Products that contain pseudoephedrine are still over-the-counter remedies, but they are now stocked behind the pharmacy counter so their sale can be more closely monitored.



pseudoephedrine (decongestant in Sudafed)

methamphetamine

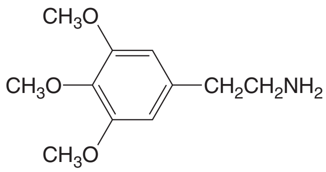
phenylephrine (decongestant in Sudafed PE)

PROBLEM 18.27

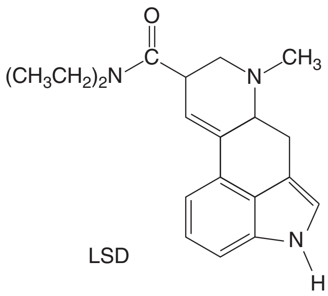
Pseudoephedrine can be readily converted to methamphetamine by replacing one OH group by a hydrogen atom. Examine the structure of phenylephrine, and suggest a reason why it cannot be readily converted to methamphetamine.

PROBLEM 18.28

Label the atoms of 2-phenylethylamine in each compound. Mescaline is the active hallucinogen in peyote, a cactus native to the southwestern United States and Mexico. LSD, commonly called "acid," was first synthesized in 1938 by Swiss chemist Albert Hoffman. Its hallucinogenic properties were first discovered when Hoffman himself ingested small amounts of the drug.

a. 

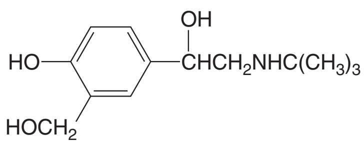
mescaline

b. 

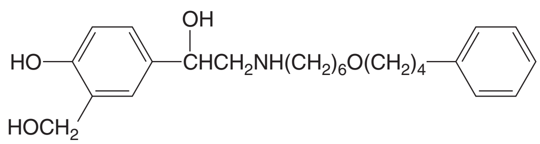
LSD

18.9B DRUGS TO TREAT ASTHMA

The search for drugs that were structurally related to epinephrine but exhibited only some components of its wide range of biological activities led to the discovery of some useful medications. Both **albuterol** and **salmeterol** are derivatives of 2-phenylethylamine that dilate lung passages; that is, they are ***bronchodilators.*** They do not, however, stimulate the heart. This makes both compounds useful for the treatment of asthma. Albuterol is a short-acting drug used to relieve the wheezing associated with asthma. Salmeterol is much longer acting, and thus it is often used before bedtime to keep an individual symptom free overnight.



albuterol
(Trade names: Ventolin, Proventil)



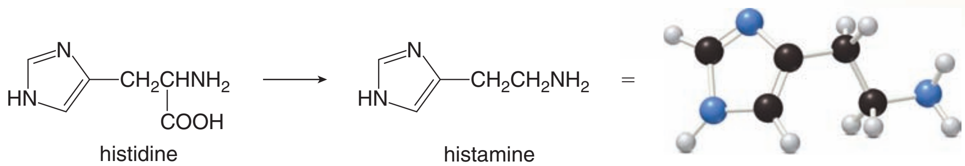
salmeterol
(Trade name: Serevent)

PROBLEM 18.29

Classify the amines and the alcohols (not the phenols) in albuterol and salmeterol as 1°, 2°, or 3°.

18.10 FOCUS ON HEALTH & MEDICINE HISTAMINE AND ANTIHISTAMINES

Histamine is a biologically active amine formed in many tissues from the amino acid histidine.



histidine histamine

Histamine is a neurotransmitter that binds to two different receptors, the H1 and H2 receptors, and produces a wide range of physiological effects on the body. Histamine is a vasodilator (it dilates capillaries), so it is released at the site of an injury or infection to increase blood flow. It

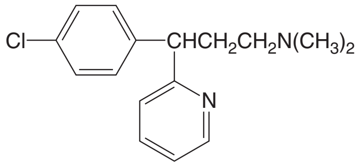
HEALTH NOTE



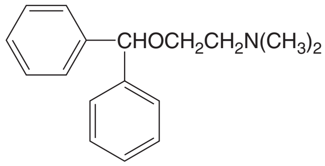
Scombroid fish poisoning, associated with facial flushing, hives, and general itching, is caused by the ingestion of inadequately refrigerated fish, typically mahimahi and tuna. Bacteria convert the amino acid histidine to histamine, and when consumed in large amounts, this clinical syndrome results.

is also responsible for the symptoms of allergies, including a runny nose and watery eyes. In the stomach, histamine stimulates the secretion of acid.

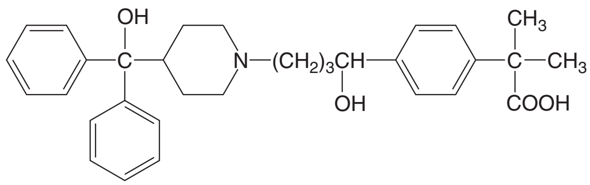
Antihistamines bind to the H1 histamine receptor, but they evoke a different response. An antihistamine like chlorpheniramine or diphenhydramine, for example, inhibits vasodilation, so it is used to treat the symptoms of the common cold and environmental allergies. These antihistamines also cause drowsiness by crossing the blood–brain barrier and binding to H1 receptors in the central nervous system. Newer antihistamines like fexofenadine (trade name: Allegra) also bind to H1 receptors, but they do not cause drowsiness because they cannot cross the blood–brain barrier and bind to the H1 receptors in the central nervous system.



chlorpheniramine
(antihistamine)

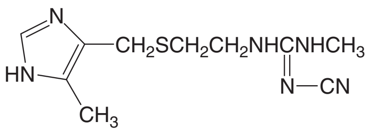


diphenhydramine
(antihistamine)



fexofenadine
(nonsedating antihistamine)

Drugs that bind to the H2 receptor produce a different effect. For example, cimetidine (trade name: Tagamet) binds to the H2 histamine receptor and, as a result, reduces acid secretion in the stomach. Thus, cimetidine is an effective **anti-ulcer** medication.



cimetidine
(Trade name: Tagamet)
anti-ulcer drug

PROBLEM 18.30 Draw a complete structure for cimetidine including all lone pairs on heteroatoms.

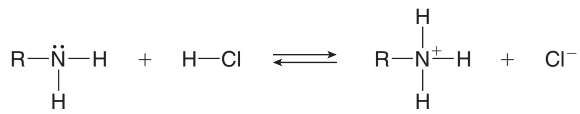
CHAPTER HIGHLIGHTS

KEY TERMS

Alkaloid (18.4)
Amine (18.1)
Ammonium salt (18.6)
Antihistamine (18.10)
Anti-ulcer drug (18.10)
Axon (18.8)
Dendrite (18.8)
Heterocycle (18.1)
Hormone (18.9)
Neuron (18.8)
Neurotransmitter (18.8)
Postsynaptic neuron (18.8)
Presynaptic neuron (18.8)
Primary (1°) amine (18.1)
Quaternary ammonium ion (18.1)
Secondary (2°) amine (18.1)
SSRI (18.8)
Synapse (18.8)
Tertiary (3°) amine (18.1)
Vesicle (18.8)

KEY REACTIONS

Amines react as bases with inorganic and organic acids (18.6).



KEY CONCEPTS

1 What are the characteristics of amines? (18.1, 18.3)

- Amines are organic nitrogen compounds, formed by replacing one or more hydrogen atoms of NH_3 by alkyl groups.
- Primary (1°) amines have one C—N bond; 2° amines have two C—N bonds; 3° amines have three C—N bonds.
- An amine has a lone pair of electrons on the N atom, and is trigonal pyramidal in shape.
- Amines contain polar C—N and N—H bonds. Primary (1°) and 2° amines can hydrogen bond. Intermolecular hydrogen bonds between N and H are weaker than those between O and H.
- Tertiary (3°) amines have lower boiling points than 1° and 2° amines since they cannot hydrogen bond.

2 How are amines named? (18.2)

- Primary (1°) amines are identified by the suffix *-amine*.
- Secondary (2°) and 3° amines with identical alkyl groups are named by adding the prefix *di-* or *tri-* to the name of the 1° amine.
- Secondary (2°) and 3° amines with different alkyl groups are named as *N*-substituted 1° amines.

3 What are alkaloids? Give examples of common alkaloids. (18.4, 18.5)

- Alkaloids are naturally occurring amines isolated from plant sources.
- Examples of alkaloids include caffeine (from coffee and tea), nicotine (from tobacco), morphine and codeine (from the opium poppy), quinine (from the cinchona tree), and atropine (from the deadly nightshade plant).

4 What products are formed when an amine is treated with acid? (18.6)

- Amines act as proton acceptors in water and acid. For example, the reaction of RNH_2 with HCl forms the water-soluble ammonium salt $RNH_3^+ Cl^-$.

5 What are the characteristics of ammonium salts and how are they named? (18.6, 18.7)

- An ammonium salt consists of a positively charged ammonium ion and an anion.
- An ammonium salt is named by changing the suffix *-amine* of the parent amine to the suffix *-ammonium* followed by the name of the anion.
- Ammonium salts are water-soluble solids.
- Water-insoluble amine drugs are sold as their ammonium salts to increase their solubility in the aqueous environment of the blood.

6 What are neurotransmitters and how do they differ from hormones? (18.8, 18.9)

- A neurotransmitter is a chemical messenger that transmits a nerve impulse from a neuron to another cell.
- A hormone is a compound produced by an endocrine gland that travels through the bloodstream to a target tissue or organ.

7 What roles do dopamine and serotonin play in the body? (18.8)

- Dopamine affects movement, emotions, and pleasure. Too little dopamine causes Parkinson's disease. Too much dopamine causes schizophrenia. Dopamine plays a role in addiction.
- Serotonin is important in mood, sleep, perception, and temperature regulation. A deficiency of serotonin causes depression. SSRIs are antidepressants that effectively increase the concentration of serotonin.

8 Give examples of important derivatives of 2-phenylethylamine. (18.9)

- Derivatives of 2-phenylethylamine contain a benzene ring bonded to a two-carbon chain that is bonded to a nitrogen atom.
- Examples of 2-phenylethylamine derivatives include epinephrine, norepinephrine, amphetamine, and methamphetamine. Albuterol and salmeterol are also derivatives of 2-phenylethylamine that are used to treat asthma.

9 What is histamine, and how do antihistamines and anti-ulcer drugs work? (18.10)

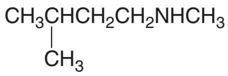
- Histamine is an amine with a wide range of physiological effects. Histamine dilates capillaries, is responsible for the runny nose and watery eyes of allergies, and stimulates the secretion of stomach acid.
- Antihistamines bind to the H1 histamine receptor and inhibit vasodilation, so they are used to treat the symptoms of colds and allergies.
- Anti-ulcer drugs bind to the H2 histamine receptor and reduce the production of stomach acid.

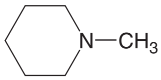
PROBLEMS

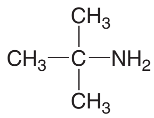
Selected in-chapter and end-of-chapter problems have brief answers provided in Appendix B.

Structure and Bonding

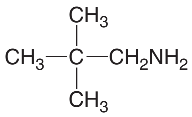
18.31 Classify each amine as 1°, 2°, or 3°.

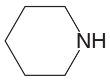
a. 

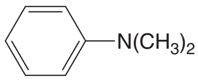
b. 

c. 

18.32 Classify each amine as 1°, 2°, or 3°.

a. 

b. 

c. 

18.33 Draw the structure of a compound that fits each description:

a. a 1° amine with molecular formula $C_5H_{13}N$
b. a 2° amine with molecular formula $C_6H_{15}N$
c. a 3° amine with molecular formula $C_6H_{13}N$
d. a quaternary ammonium ion with molecular formula $C_8H_{20}N^+$

18.34 Draw the structure of a compound of molecular formula $C_4H_{11}NO$ that fits each description:

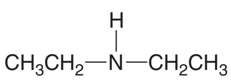
a. a compound that contains a 1° amine and a 1° alcohol
b. a compound that contains a 2° amine and a 2° alcohol
c. a compound that contains a 1° amine and a 3° alcohol
d. a compound that contains a 3° amine and a 1° alcohol

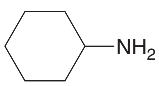
18.35 What is the difference between a 3° amine and a 3° alcohol? Give an example of each compound that contains six carbons.

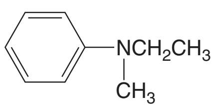
18.36 What is the difference between a 3° amine and a 3° amide? Give an example of each compound that contains six carbons.

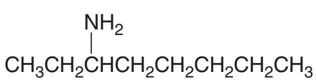
Nomenclature

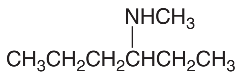
18.37 Give an acceptable name for each amine.

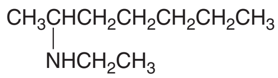
a. 

b. 

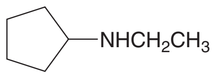
c. 

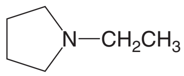
d. 

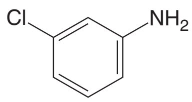
e. 

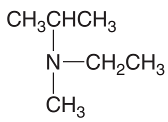
f. 

18.38 Give an acceptable name for each amine.

a. $CH_3(CH_2)_6NH_2$
b. $CH_3CH_2CH_2CH_2CH_2N(CH_3)_2$
c. 

d. 

e. 

f. 

18.39 Draw the structure corresponding to each name.

a. 1-decanamine
b. tricyclohexylamine
c. *p*-bromoaniline
d. 3-aminobutanoic acid
e. *N*,*N*-dipropyl-2-octanamine
f. *N*-ethylhexylamine

18.40 Draw the structure corresponding to each name.

a. cyclobutylamine
b. 4-nonanamine
c. *N*-pentylaniline
d. 3-amino-2-butanone
e. 3-methyl-1-butanamine
f. *N*-ethyl-*N*-propylcyclopentylamine

18.41 What is the difference between *N*,*N*-dimethylaniline and 2,4-diethylaniline? Draw structures to illustrate the difference.

18.42 What is the difference between *N*-butylaniline and *o*-butylaniline? Draw structures to illustrate the difference.

18.43 Draw the structure of each ammonium salt.

a. dipropylammonium chloride
b. butylammonium bromide
c. ethyldimethylammonium hydroxide

18.44 Draw the structure of each ammonium salt.

a. cyclohexylammonium fluoride
b. triethylammonium iodide
c. ethylmethylammonium chloride

18.45 Draw the structures for the four amines of molecular formula C_3H_9N. Give the systematic name for each amine.

18.46 (a) Draw the structures for the eight constitutional isomers of molecular formula $C_4H_{11}N$. (b) Give the systematic name for each amine. (c) Identify the chirality center present in one of the amines.

Physical Properties and Intermolecular Forces

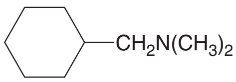
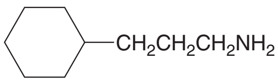
18.47 Explain why pyridine is more water soluble than benzene. How would you expect the boiling point of pyridine and benzene to compare?

18.48 Explain why $CH_3CH_2CH_2NH_2$ is water soluble but $CH_3CH_2CH_2CH_3$ is not water soluble.

18.49 Which compound in each pair has the higher boiling point?

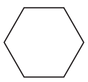
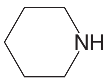
a. $CH_3CH_2CH_2NH_2$ or $CH_3(CH_2)_7NH_2$

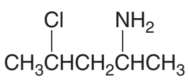
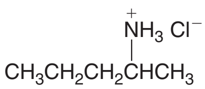
b. $CH_3(CH_2)_6OH$ or $CH_3(CH_2)_6NH_2$

c.  or 

18.50 Which compound in each pair has the higher boiling point?

a. $(CH_3CH_2)_2C{=}O$ or $(CH_3CH_2)_2CHNH_2$

b.  or 

c.  or 

18.51 Draw the hydrogen bonding interactions that occur between two molecules of diethylamine [$(CH_3CH_2)_2NH$].

18.52 Draw the hydrogen bonding interactions that occur between diethylamine [$(CH_3CH_2)_2NH$] and water.

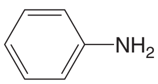
18.53 Explain why a 1° amine and a 3° amine having the same number of carbons are soluble in water to a similar extent, but the 1° amine has a higher boiling point.

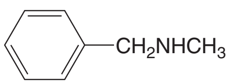
18.54 Which compound has the higher water solubility: $CH_3(CH_2)_5NH_2$ or $CH_3(CH_2)_5NH_3^+\ Cl^-$? Explain your choice.

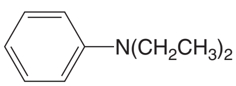
Acid–Base Reactions of Amines

18.55 Draw the acid–base reaction that occurs when each amine dissolves in water: (a) $CH_3CH_2NH_2$; (b) $(CH_3CH_2)_2NH$; (c) $(CH_3CH_2)_3N$.

18.56 What ammonium salt is formed when each amine is treated with HCl?

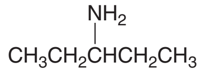
a. 

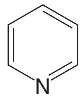
b. 

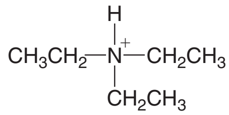
c. 

18.57 Draw the products of each acid–base reaction.

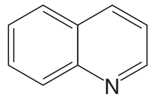
a. $CH_3CH_2CH_2N(CH_3)_2 + HCl \longrightarrow$

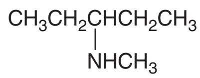
b.  $+ H_2SO_4 \longrightarrow$

c.  $+ HBr \longrightarrow$

d.  $+ NaOH \longrightarrow$

18.58 Draw the products of each acid–base reaction.

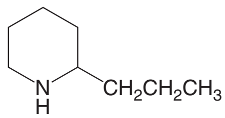
a.  $+ HCl \longrightarrow$

b.  $+ H_2SO_4 \longrightarrow$

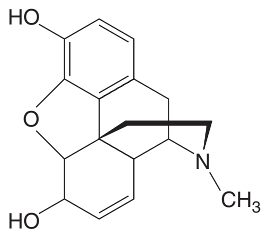
c. $CH_3NH_2 + CH_3COOH \longrightarrow$

d. $CH_3(CH_2)_5\overset{+}{N}H_3 + NaOH \longrightarrow$

18.59 What ammonium salt is formed when each alkaloid is treated with HCl?

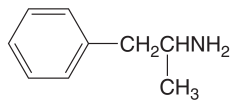
a. 

coniine

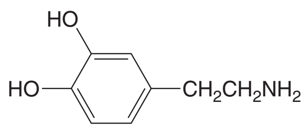
b. 

morphine

18.60 What ammonium salt is formed when each biologically active amine is treated with H_2SO_4?

a. 

amphetamine

b. 

dopamine

Neurotransmitters, Alkaloids, and Other Biologically Active Amines

18.61 What type of nitrogen heterocycle occurs in both coniine and morphine (Problem 18.59)?

18.62 Only one of the N atoms in nicotine has a trigonal pyramidal shape. Identify which N is trigonal pyramidal and explain why the other N atom has a different molecular shape.

18.63 What physiological effects does caffeine produce on the body?

18.64 Why should caffeine intake be limited in pregnant and nursing mothers?

18.65 Why are aqueous solutions of an alkaloid slightly basic?

18.66 For each alkaloid, list its natural source and give one of its uses in medicine: (a) morphine; (b) quinine; (c) atropine.

18.67 What is the difference between a presynaptic neuron and a postsynaptic neuron?

18.68 Besides the cell body, what are the important parts of a neuron?

18.69 What are the physiological effects of dopamine? What conditions result when dopamine levels are too high or too low?

18.70 Explain why patients with Parkinson's disease cannot be treated by giving them dopamine, even though the disease results from low dopamine levels.

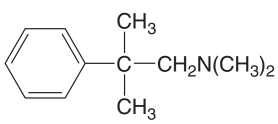
18.71 What are the physiological effects of serotonin? What condition results when there is too little serotonin?

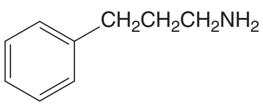
18.72 Give two examples of SSRIs and explain how they combat depression.

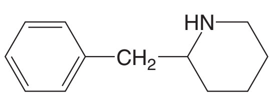
18.73 In the body, what amino acid is used to synthesize each compound: (a) dopamine; (b) norepinephrine; (c) serotonin; (d) histamine?

18.74 What is the difference between a neurotransmitter and a hormone?

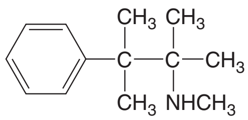
18.75 Which of the following amines are derivatives of 2-phenylethylamine? Label the atoms of 2-phenylethylamine in those amines that contain this unit.

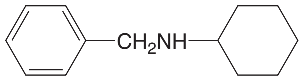
a. 

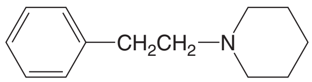
b. 

c. 

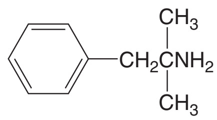
18.76 Which of the following amines are derivatives of 2-phenylethylamine? Label the atoms of 2-phenylethylamine in those amines that contain this unit.

a. 

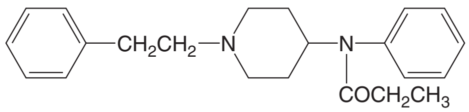
b. 

c. 

18.77 Locate the atoms of 2-phenylethylamine in each drug.

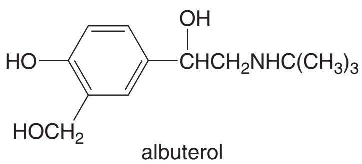
a. 

phentermine
(one component of fen–phen, a banned diet drug)

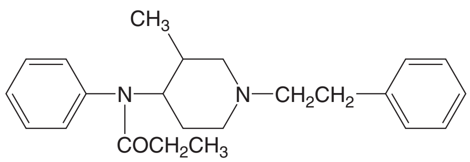
b. 

fentanyl
(a narcotic pain reliever)

18.78 Locate the atoms of 2-phenylethylamine in each drug.

a. 

albuterol
(asthma drug)

b. 

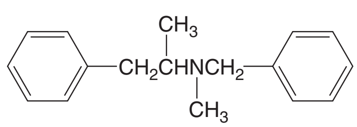
3-methylfentanyl
(street drug, 3,000 times more potent than morphine)

18.79 Give an example of an antihistamine. Explain how an antihistamine relieves the runny nose and watery eyes of a cold or allergies.

18.80 Give an example of an anti-ulcer drug, and explain how it is used to treat a stomach ulcer.

General Questions

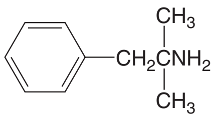
18.81 Benzphetamine (trade name: Didrex) is a habit-forming diet pill with many of the same properties as amphetamine.



benzphetamine

a. Label the amine as 1°, 2°, or 3°.
b. Label the chirality center in benzphetamine.
c. Draw the two enantiomers of benzphetamine.
d. Draw a constitutional isomer that contains a 1° amine.
e. Draw a constitutional isomer that contains a 3° amine.
f. Draw the structure of benzphetamine hydrochloride.
g. What products are formed when benzphetamine is treated with acetic acid, CH_3COOH?

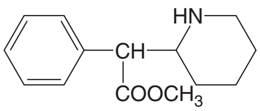
18.82 Phentermine is one component of the banned diet drug fen–phen.



phentermine

a. Label the amine as 1°, 2°, or 3°.
b. Indicate the molecular shape around each atom.
c. Draw a constitutional isomer that contains a 1° amine.
d. Draw a constitutional isomer that contains a 2° amine.
e. Draw the structure of phentermine hydrobromide.
f. What products are formed when phentermine is treated with benzoic acid, C_6H_5COOH?

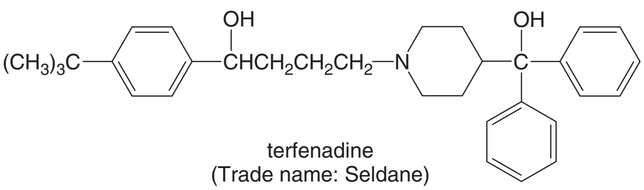
18.83 Ritalin is the trade name for methylphenidate, a drug used to treat attention deficit hyperactivity disorder (ADHD).



methylphenidate
(Trade name: Ritalin)

a. Identify the functional groups.
b. Label the amine as 1°, 2°, or 3°.
c. Locate the chirality centers.
d. Locate the atoms of 2-phenylethylamine.
e. Draw the structure of methylphenidate hydrochloride.

18.84 Seldane is the trade name for terfenadine, an antihistamine once used in the United States but withdrawn from the market because of cardiac side effects observed in some patients.

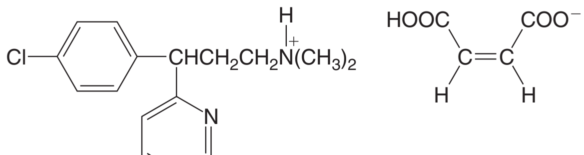


terfenadine
(Trade name: Seldane)

a. Identify the functional groups.
b. Label the amine as 1°, 2°, or 3°.
c. Label any alcohol as 1°, 2°, or 3°.
d. Label any 4° carbon.
e. Locate any chirality centers.
f. Draw the structure of terfenadine hydrochloride.

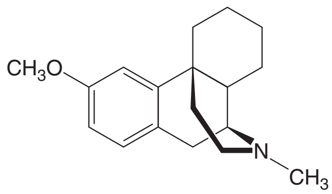
Applications

18.85 The antihistamine in the over-the-counter product Chlortrimeton is chlorpheniramine maleate. Draw the structure of the amine and carboxylic acid that are used to form this ammonium salt.



chlorpheniramine maleate

18.86 Dextromethorphan hydrobromide is a cough suppressant used in many over-the-counter cough and cold medications. Given the structure of the parent amine dextromethorphan, what is the structure of its hydrobromide salt?



dextromethorphan

18.87 What is the difference between a vasodilator and a bronchodilator? Give an example of a drug that fits each category.

18.88 Why do some antihistamines cause drowsiness while others do not?

18.89 In Section 17.7 we learned that aspirin exists in different forms (neutral or ionic) in the stomach and the intestines. Similar behavior occurs with amines that are ingested, since they undergo acid–base reactions. In what form does the drug albuterol (Section 18.9B) exist in the stomach? In the intestines?

18.90 Explain why eating a poppy seed bagel can produce a positive test in a drug screening.

CHALLENGE QUESTIONS

18.91 Compare the structures of morphine and heroin. Suggest a method to convert morphine to heroin.

18.92 Heroin and the morphine from which it is made are both odorless solids. Drug-sniffing dogs can sometimes locate heroin because of a biting odor that is present in a small enough concentration that humans cannot detect, but the keen nose of a canine can. Suggest what compound might cause the odor that allows for heroin detection. (Hint: What products would be formed by the hydrolysis of heroin in moist air?)